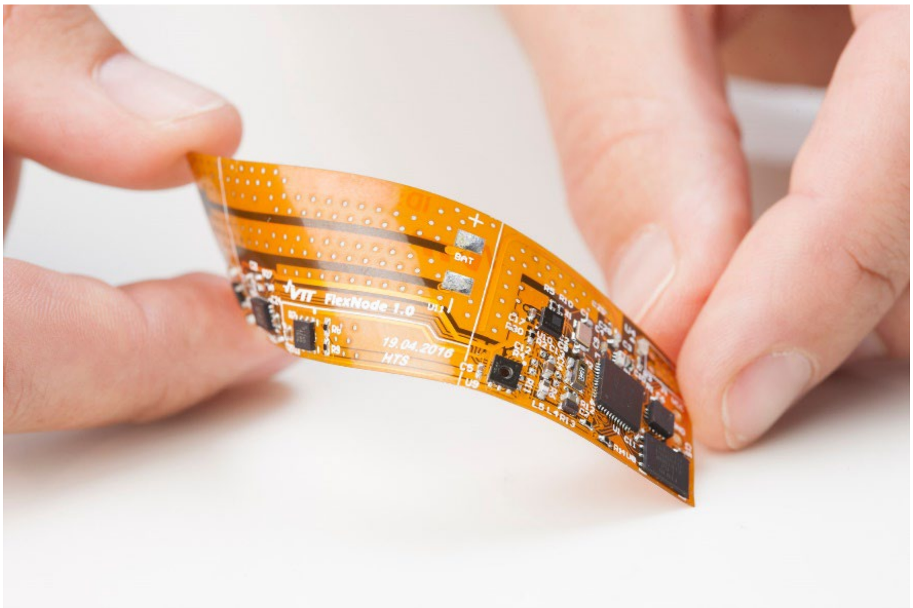
RESEARCH REPORT

VTT-R-00067-26



Experimental test results of XLPE: Virgin and aged samples

Authors:	Nikhil Verma
Confidentiality:	VTT Public
Version:	29.01.2026

beyond the obvious

Report's title

Experimental test results of XLPE: Virgin and aged samples

Customer, contact person, address	**Order reference**
State Nuclear Waste Management Fund (VYR) SAFER2028 Programme	
Project name	**Project number/Short name**
Fire behaviour and safety of nuclear infrastructure	140712/FASAANI
Author(s)	**Pages**
Nikhil Verma	45
Keywords	**Report identification code**
Pyrolysis, polyethylene, XLPE, TGA, Thermogravimetric analysis	VTT-R-00067-26

Summary

This work investigates the thermal degradation and fire behaviour of cross-linked polyethylene (XLPE) through a coordinated set of micro-scale (TGA/DSC) and bench-scale (cone calorimeter) experiments. Virgin and artificially aged XLPE samples manufactured from the same base material were tested to generate a consistent, multi-scale dataset suitable for fire-safety analysis and computational modelling. The study was conducted within Task 2.2 of the FASAANI project under the SAFER2028 programme and addresses experimental needs identified in the earlier SAFIR2022 URAN project.

The results show that slow thermal aging at moderate temperatures alters the kinetics of XLPE degradation, thereby shifting degradation onset and early mass-loss behaviour, without changing the fundamental decomposition mechanism. Aged XLPE displays slightly earlier degradation and greater oxidative sensitivity but still produces minimal char, confirming the low residue yield characteristic of this material. Fast-aged samples, exposed to unrealistically high temperatures, showed significant pre-damage and were therefore excluded from the primary fire behaviour assessment.

Under realistic fire conditions (air with external ignition), slow-aged XLPE consistently produced higher peak heat release rates and faster growth to peak burning compared to virgin material, indicating more intense but shorter-lived flaming combustion. Additional test configurations under air without ignition and under nitrogen provide complementary datasets for future studies of self-ignition and pure pyrolysis behaviour.

Overall, the findings demonstrate that thermal aging can intensify the fire behaviour of unmodified XLPE. It should be noted, however, that the present results apply to the specific XLPE material studied. Different XLPE grades and formulations, particularly variations in antioxidant type and content, may exhibit different aging and degradation behaviour. Overall, the resulting dataset offers a robust basis for developing and validating computational material models needed for fire-safety assessment of long-term-used XLPE-based cables in nuclear power plants.

Confidentiality	VTT Public

Espoo 30.1.2026

Written by	**Reviewed by**
Nikhil Verma (Research Scientist)	Napat Vajragupta (Research Team Leader)

VTT's contact address

Nikhil Verma, P.O. Box 1000, FI-02044 VTT, Finland, nikhil.verma @vtt.fi

Distribution (customer and VTT)

SAFER2028 TAG 1.1
VTT

Approval

VTT TECHNICAL RESEARCH CENTRE OF FINLAND LTD

Date:	30 January 2026
Signature:	**Signed by:** 88A44463BFC1495...
Name:	Napat Vajragupta
Title:	Research Team Leader, BA5503

Preface

This work has been carried out as a part of work package 2 of FASAANI project which is one of the projects in the SAFER2028. The work covers the task 2.2 of the project. Thanks are extended to the State Nuclear Waste Management Fund (VYR) and as well as other key organisations operating in the field of nuclear energy in Finland for funding the project work.

29.01.2026

Nikhil Verma, Espoo

Contents

1. Introduction

The experimental results presented in this report stem from Task 2.2 of the FASAANI project, which is part of the Finnish SAFER2028 research programme. This work was initiated based on findings from the earlier Finnish SAFIR2022 research programme project URAN, particularly its Task 2.2. The overall objective of the present research is to enhance the safety of Finland's nuclear infrastructure, with a particular emphasis on fire safety of XLPE-based cables in nuclear power plants (NPPs).

Electrical cables represent one of the most significant fire loads in NPPs. Within this category, power cables are especially important in fire risk assessments of nuclear facilities. A wide range of power cables is used in NPPs, many of which employ cross-linked polyethylene (XLPE) as their electrical insulation material. The task of the FASAANI project addressed in this report focuses specifically on the fire safety characteristics of XLPE used as insulation material in power cables.

Although some research exists on the fire behaviour of XLPE-insulated cables in their "virgin" state, that is, when they are relatively new, considerably less is known about the properties of such cables after decades of service in NPP environments. In Finland, nuclear power plants typically operate for at least 50 years. For instance, the Loviisa nuclear power plants were commissioned in the late 1970s, and their operating licences may be extended by an additional 20 years, resulting in a total operational lifetime of up to 70 years. Over such overall periods, polymeric materials such as XLPE are subject to ageing due to plant environmental conditions. During service, cables are exposed to oxygen (air) and may also experience humidity, ionising and electromagnetic radiation, elevated temperatures above ambient conditions, mechanical stresses, and other ageing factors, all of which can affect their fire performance and safety characteristics.

The work reported here does not aim to address all aspects of power cable ageing in NPPs. Instead, the focus is placed specifically on the ageing behaviour of the XLPE insulation material itself. Accordingly, this report presents experimental research on the ageing of XLPE. Part of the work has already been reported in the previous annual report of this task (Helminen et al., 2024). The present report further reports the experiments and analyses conducted during the current reporting period.

The primary aim of the current task is not to draw comprehensive conclusions, but rather to increase the available experimental data on XLPE and its artificially aged counterparts. In the SAFIR2022–URAN project, it was identified that additional experimental information was needed to complement the SAFIR2022–SAMPO data. Preliminary attempts were made to identify such information through a limited literature search; however, the intention was not to conduct a comprehensive literature review, but rather to locate potentially useful reference data. A key issue identified was the lack of comprehensive experimental datasets obtained from the same XLPE material across multiple scales, ranging from microscale to full-scale experiments, including detailed information on oxygen-related reactions occurring during combustion in open air. The present work aims to address such gap with experimental data.

To this end, microscale and intermediate-scale experiments were conducted on the same XLPE material within the scope of the present project. The experiments were performed under different atmospheric conditions to enable understanding of thermal degradation and oxidation of virgin XLPE and its artificially aged counterpart, i.e., aged XLPE. Thus, the main outcome of Task 2.2 of the FASAANI project is a set of experimental results for virgin and aged XLPE, providing insight into its degradation and combustion behaviour as a base material in fires involving XLPE-insulated cables. The experiments and their results are presented on an "as-is" basis.

The experimental programme comprised the following activities:

- Small samples extracted from virgin XLPE material were tested using TGA/DSC equipment at the VTT facilities in Tampere.
- Virgin XLPE samples were tested using a cone calorimeter at Aalto University.
- Slow ageing (thermal) of XLPE samples was carried out at Aalto University.

- Small samples extracted from thermally aged XLPE materials were tested using TGA/DSC equipment at the VTT facilities in Tampere.
- Thermally aged XLPE samples were tested using a cone calorimeter at Aalto University.

Based on the experimental results, a qualitative comparison has been performed to identify any observable differences in the degradation and combustion behaviour between virgin and aged XLPE samples.

In addition to the main experimental programme, supplementary (“side”) tests were conducted. These included fast ageing of XLPE samples under TGA conditions, as previously reported in Helminen et al. (2024). Furthermore, fast ageing (thermal) at high temperature of an additional XLPE sample was also carried out at Aalto University using a hot oven.

2. Micro-scale experimental data of the XLPE material (TGA/DSC)

The pyrolysis of the XLPE material produced as described in Appendix A (Fabrication of the XLPE sheets) was studied using combined TGA/DSC device. The pyrolysis processes were studied for both virgin sample and aged sample. In addition to the three test sets that were reported already in the year 2024 report, two additional test sets were done as follows:

1. Experiments of the slow-aged XLPE sheets:
    a. Virgin XLPE samples were slowly aged for 16 weeks in an oven at 140 °C.
    b. Small pieces of sample (micrograms sized samples) were cut from slow-aged XLPE samples for TGA/DSC tests.
    c. TGA/DSC tests: four different heating rates for N_2 and two different heating rates O_2 atmospheres used.
2. Experiments of the fast-aged XLPE sheets:
    a. Virgin XLPE samples were fast aged for four hours in an oven at 220 °C.
    b. Small pieces of sample (micrograms sized samples) were cut from fast-aged XLPE samples.
    c. TGA/DSC tests: four different heating rates for N_2 and two different heating rates O_2 atmospheres used.

The Table 1 shows the test plan for TGA slow-aged samples and Table 2 shows the test plan for fast-aged samples.

Table 1. The experimental TGA/DSC campaign for the slow-aged XLPE.

ID	Atmosphere	Heating Rate (K/min)
1	N_2	5
2	N_2	5
3	N_2	10
4	N_2	10
5	N_2	20
6	N_2	20
7	N_2	30
8	N_2	30
9	O_2	10
10	O_2	10
11	O_2	20
12	O_2	20

Table 2. The experimental TGA/DSC campaign for the fast-aged XLPE.

ID	Atmosphere	Heating Rate (K/min)
1	N_2	5
2	N_2	10
3	N_2	20
4	N_2	30
5	O_2	10
6	O_2	10
7	O_2	20
8	O_2	20

2.1 TGA/DSC results of the slow-aged XLPE sheets

The individual TGA/DSC measurement results for slow-aged XLPE sheets are compiled in Appendix B. Here, separate graphs are provided for each heating rate used in the TGA experiments, allowing the influence of heating rate to be visualized for both virgin XLPE and slow-aged XLPE samples. Such layout enables a straightforward, side-by-side comparison between aged and virgin samples. For clarity, average values of repeated runs are shown on the graphs as indicated. For results related to virgin samples, the report by Helminen et al. (2024) may be consulted.

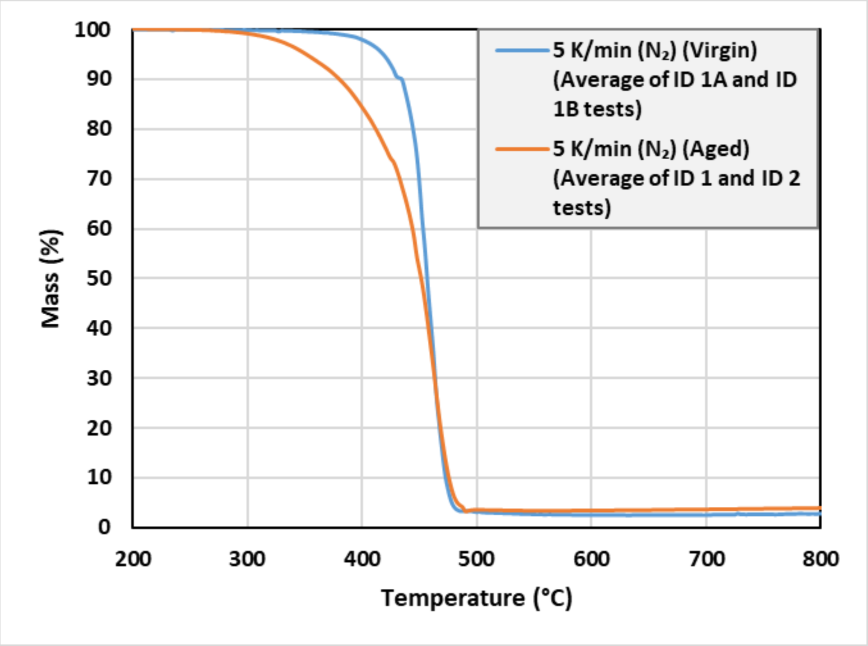


Figure 1. TGA result of mass loss of virgin XLPE sample and slow-aged XLPE sample at heating rate of 5 K/min in nitrogen.

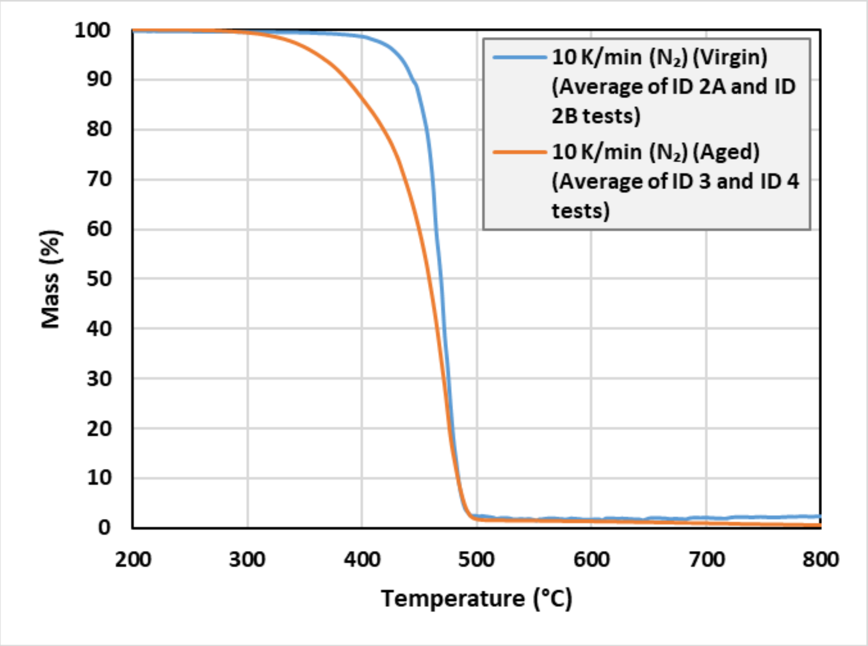


Figure 2. TGA result of mass loss of virgin XLPE sample and slow-aged XLPE sample at heating rate of 10 K/min in nitrogen.

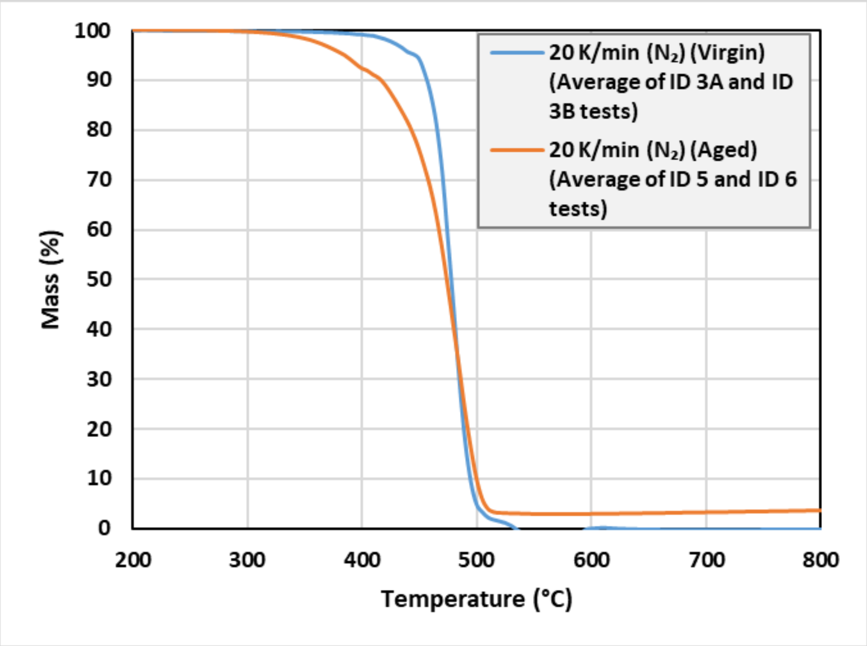


Figure 3. TGA result of mass loss of virgin XLPE sample and slow-aged XLPE sample at heating rate of 20 K/min in nitrogen.

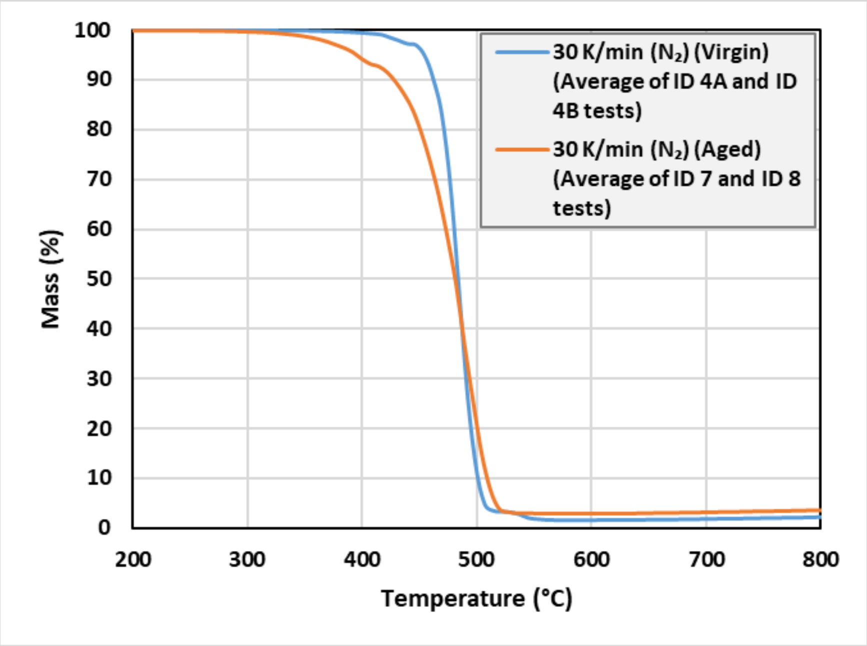


Figure 4. TGA result of mass loss of virgin XLPE sample and slow-aged XLPE sample at heating rate of 30 K/min in nitrogen.

It can be noted from Figure 1 to Figure 4 that thermal degradation of slow-aged XLPE sample starts earlier than virgin XLPE sample in nitrogen. However, higher mass loss rate is shown by virgin XLPE sample once the degradation has already started.

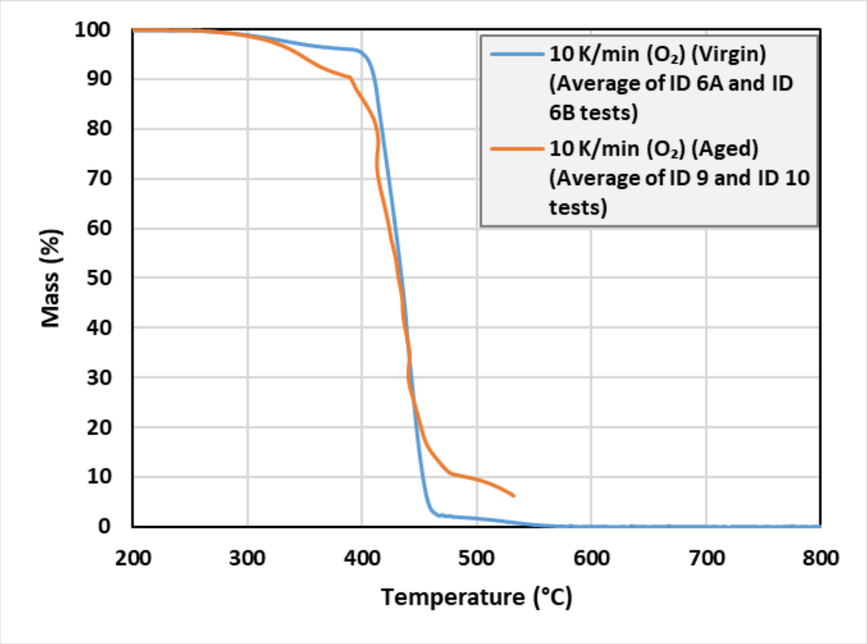


Figure 5. TGA result of mass loss of virgin XLPE sample and slow-aged XLPE sample at heating rate of 10 K/min in oxygen *(Numerical data was not available beyond ~532°C for aged slow-aged XLPE sample)*.

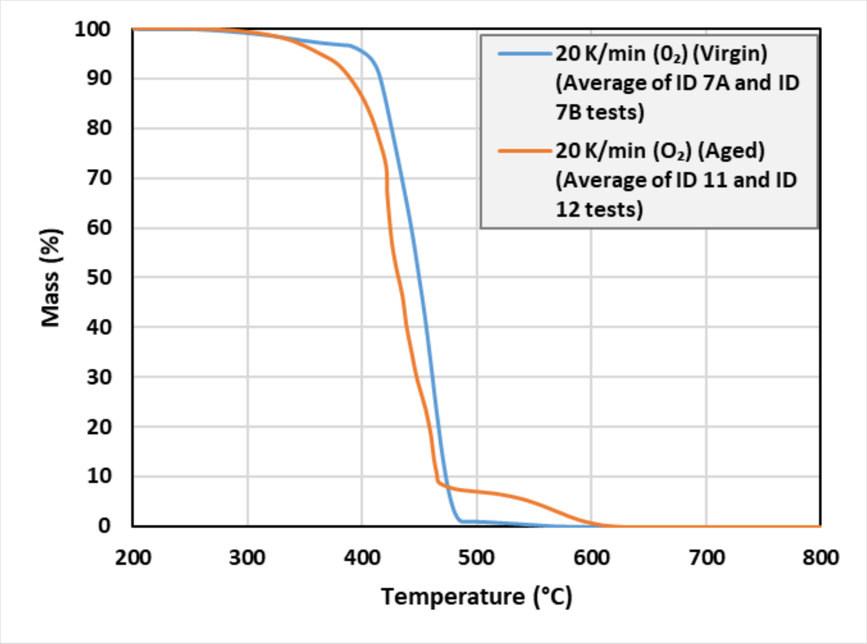


Figure 6. TGA result of mass loss of virgin XLPE sample and slow-aged XLPE sample at heating rate of 20 K/min in oxygen.

It can be noted from Figure 5 and Figure 6 that the thermal degradation of virgin XLPE sample and slow-aged XLPE sample approximately starts at around same temperature in oxygen. However, the aged XLPE sample shows steeper mass loss rate initially after the initiation of degradation.

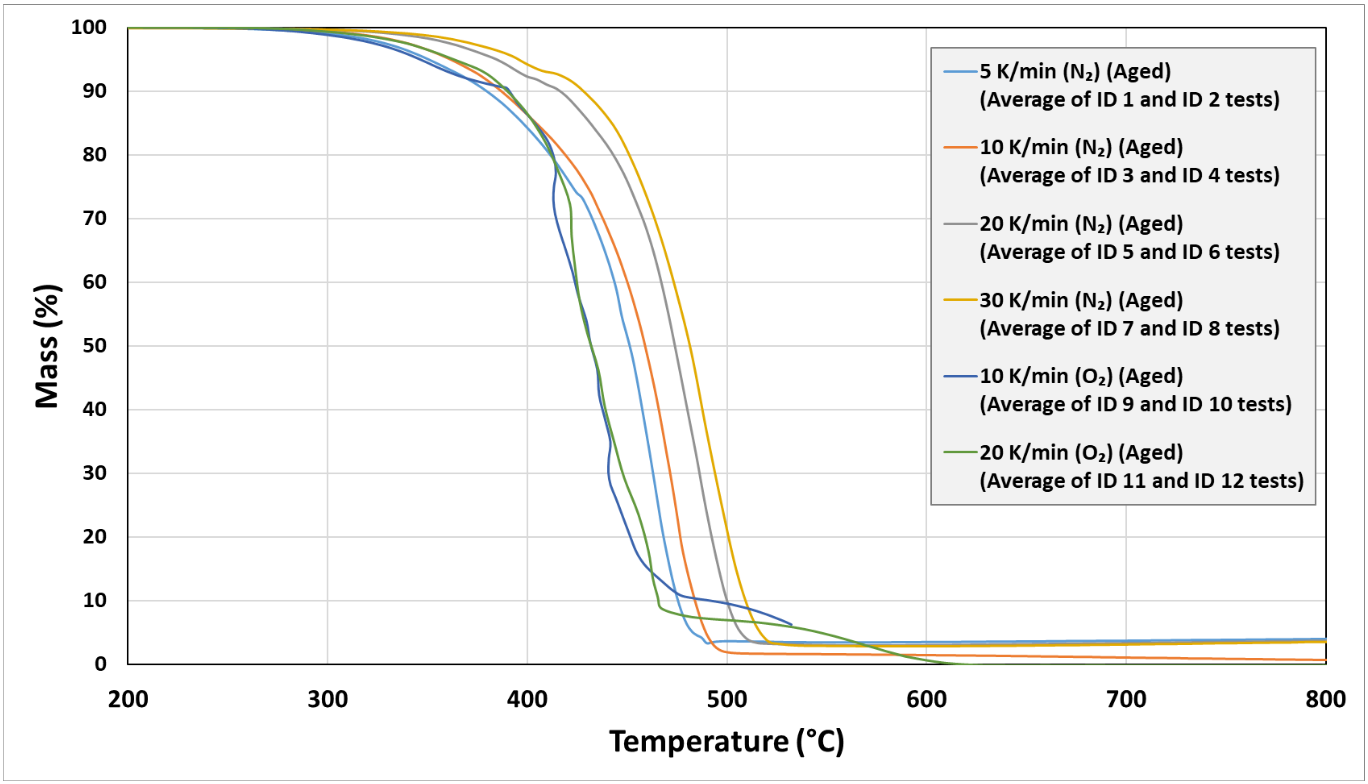


Figure 7. TGA result of mass loss of slow-aged XLPE sample all together at different heating rates in nitrogen and oxygen.

From Figure 7 it can be noted that the TGA results collectively demonstrate that slow-aged XLPE follows a consistent thermal degradation pattern across a range of heating rates and atmospheric conditions. Regardless of test parameters, the polymer maintains its mass stability up to approximately 350–400°C, after which it undergoes rapid decomposition. The influence of heating rate is clearly visible: higher heating rates shift the apparent onset of decomposition to higher temperatures. Such behaviour aligns with general kinetic principles, where faster heating delays the apparent initiation of degradation and compresses the decomposition process into a narrower temperature window. In contrast, lower heating rates allow more time for early-stage breakdown, resulting in slightly earlier onset temperatures and more gradual mass loss. Atmosphere also plays a notable role. Under oxygen, degradation progresses somewhat earlier compared to nitrogen, reflecting the oxidative sensitivity of XLPE. The presence of oxygen accelerates possibly the chain scission and promotes a more aggressive mass-loss profile, especially in the initial stages. However, both nitrogen and oxygen conditions ultimately converge to nearly complete volatilization with minimal residue, indicating that slow-aged XLPE also exhibits low char-forming capability and is thermally less robust in terms of carbonaceous residue formation.

Overall, the results demonstrate that (slow) ageing primarily influences the start and early rate of degradation.

2.2 TGA/DSC results of the fast-aged XLPE samples

Virgin XLPE sheets were placed in a 220 °C oven for four hours to evaluate whether this type of rapid aging is feasible for large samples. The sheets were positioned horizontally on a tray because the oven temperature is significantly higher than the material's melting point. Figure 1 shows a photograph of a sheet after the high-temperature aging. It is evident that the material has undergone substantial changes compared to virgin XLPE. The sample has turned brown and appears "baked." Such transformation suggests that the aging temperature may have been too high, potentially causing pyrolysis during the process. Consequently, the rapidly aged samples like it may not accurately represent the condition of XLPE used in older NPP plants, where the material is not exposed to such high temperatures during normal operation. Therefore, the relevance of these fast-aging tests may be limited when considering typical temperature- and oxygen-driven aging of XLPE-insulated cables. However, the results may still be applicable to fire scenarios in which cables experience pre-heating before ignition. They may also be useful when assessing flame-spread behaviour along cables. Their TGA results are therefore compared with those of virgin XLPE to identify any differences in the mass-loss behaviour.

Figure 8. A XLPE sheet after the fast aging done inside an oven.

The individual TGA/DSC measurement results for fast-aged XLPE sheets are compiled in Appendix C. Here, separate graphs are provided for each heating rate used in the TGA experiments, allowing the influence of heating rate to be visualized for both virgin XLPE and fast-aged XLPE samples. Such layout enables a straightforward, side-by-side comparison between aged and virgin samples. For results related to virgin samples, the report by Helminen et al. (2024) may be consulted.

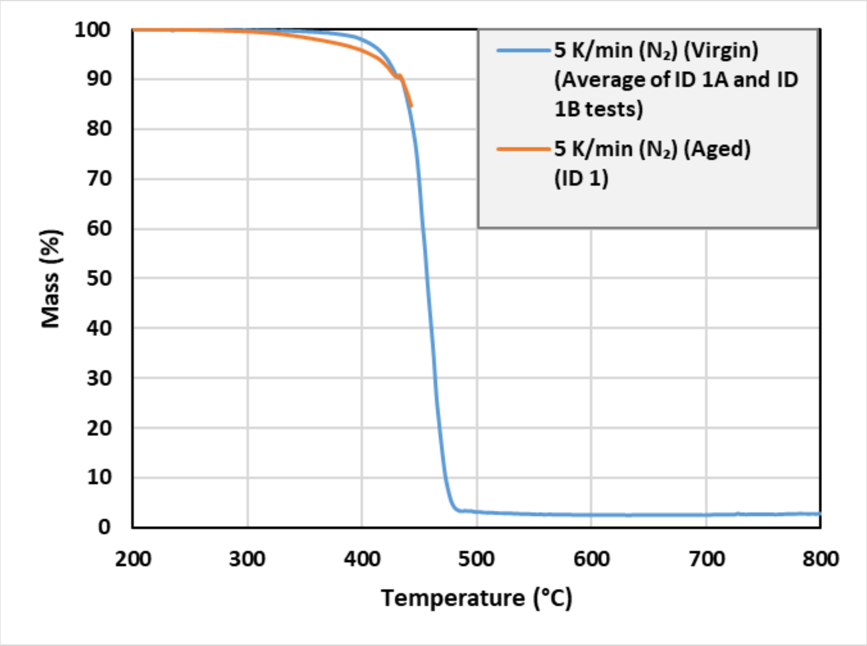


Figure 9. TGA result of mass loss of virgin XLPE sample and fast-aged XLPE sample at heating rate of 5 K/min in nitrogen (Numerical data was not available beyond ~454°C for aged fast-aged XLPE sample).

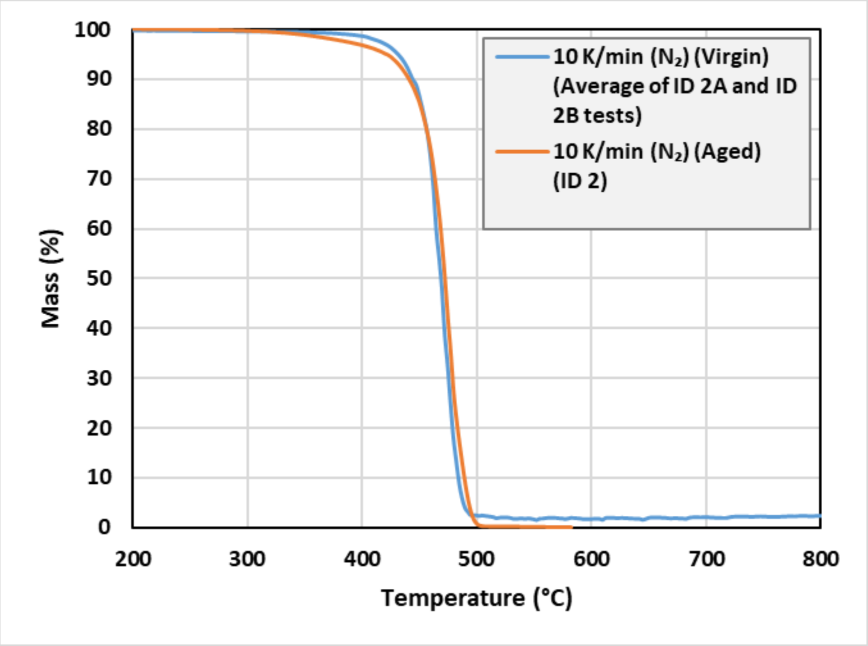


Figure 10. TGA result of mass loss of virgin XLPE sample and fast-aged XLPE sample at heating rate of 10 K/min in nitrogen.

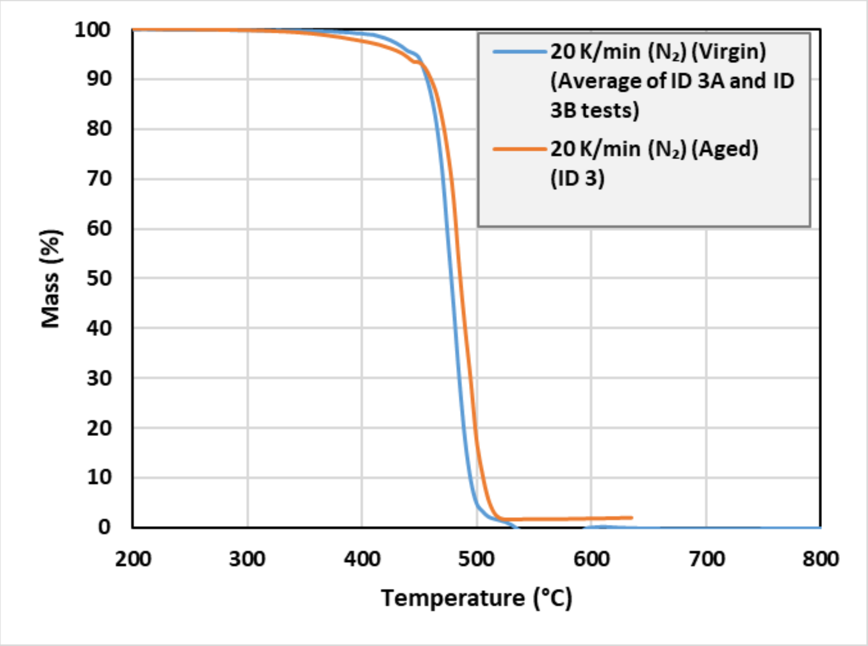


Figure 11. TGA result of mass loss of virgin XLPE sample and fast-aged XLPE sample at heating rate of 20 K/min in nitrogen.

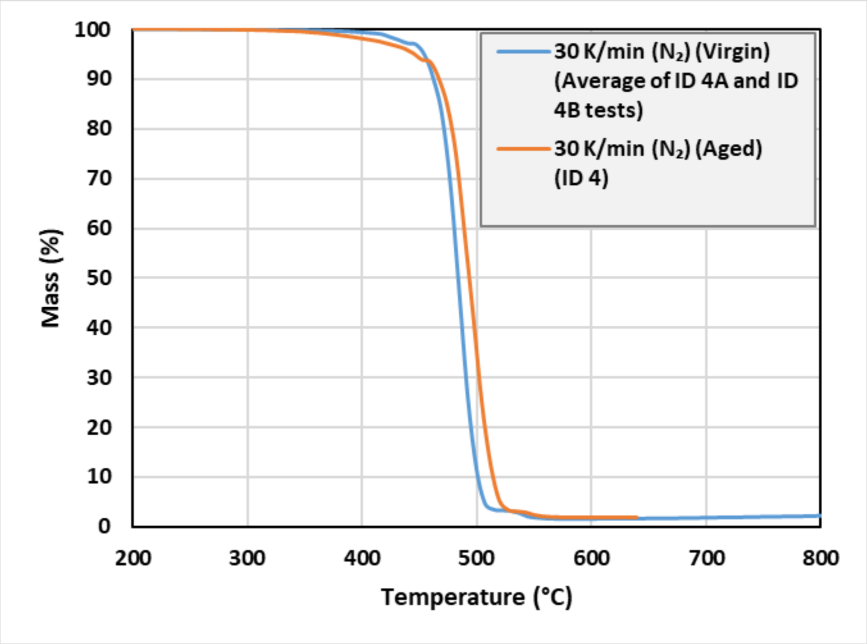


Figure 12. TGA result of mass loss of virgin XLPE sample and fast-aged XLPE sample at heating rate of 30 K/min in nitrogen.

It can be noted from Figure 9 to Figure 12 that thermal degradation of fast-aged XLPE sample starts earlier than virgin XLPE sample in nitrogen. However, higher mass loss rate is shown by virgin XLPE sample once the degradation has already started at slightly lower temperature compared to fast-aged XLPE samples.

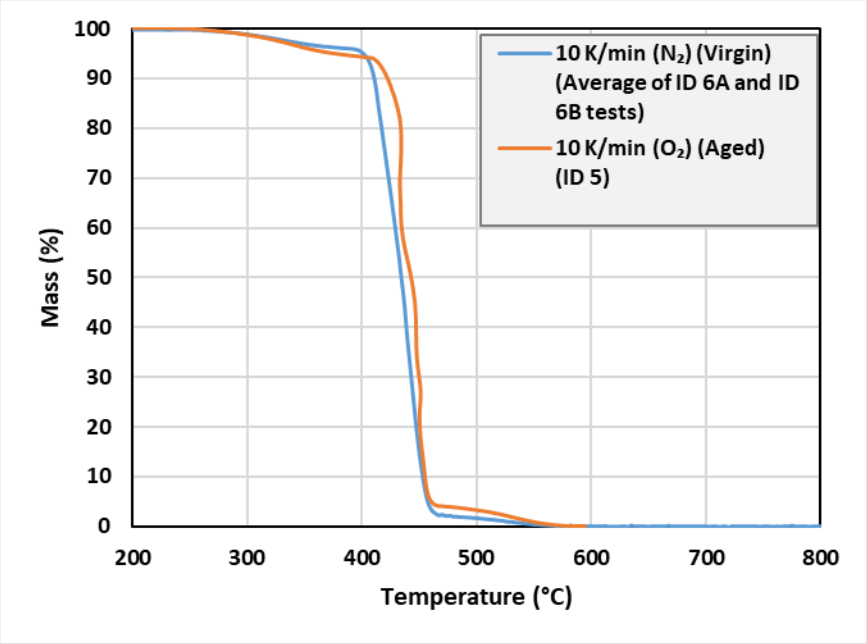


Figure 13. TGA result of mass loss of virgin XLPE sample and fast-aged XLPE sample at heating rate of 10 K/min in oxygen.

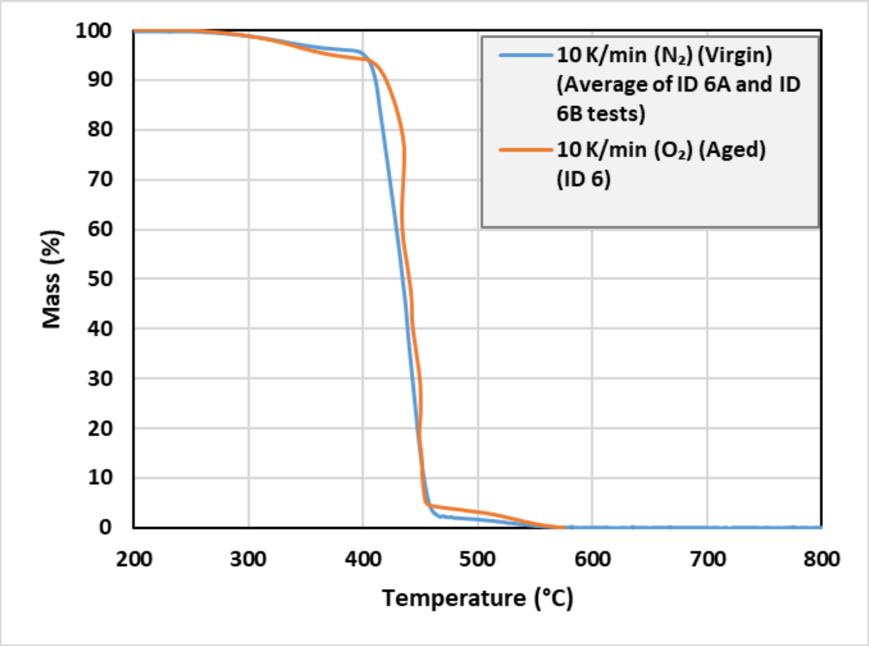


Figure 14. TGA result of mass loss of virgin XLPE sample and fast-aged XLPE sample at heating rate of 10 K/min in oxygen.

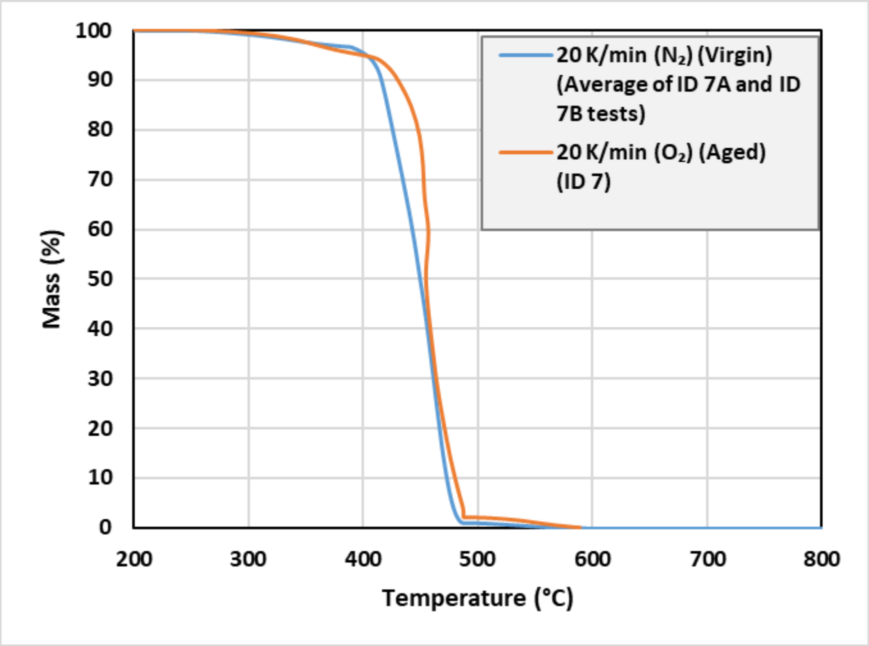


Figure 15. TGA result of mass loss of virgin XLPE sample and fast-aged XLPE sample at heating rate of 20 K/min in oxygen.

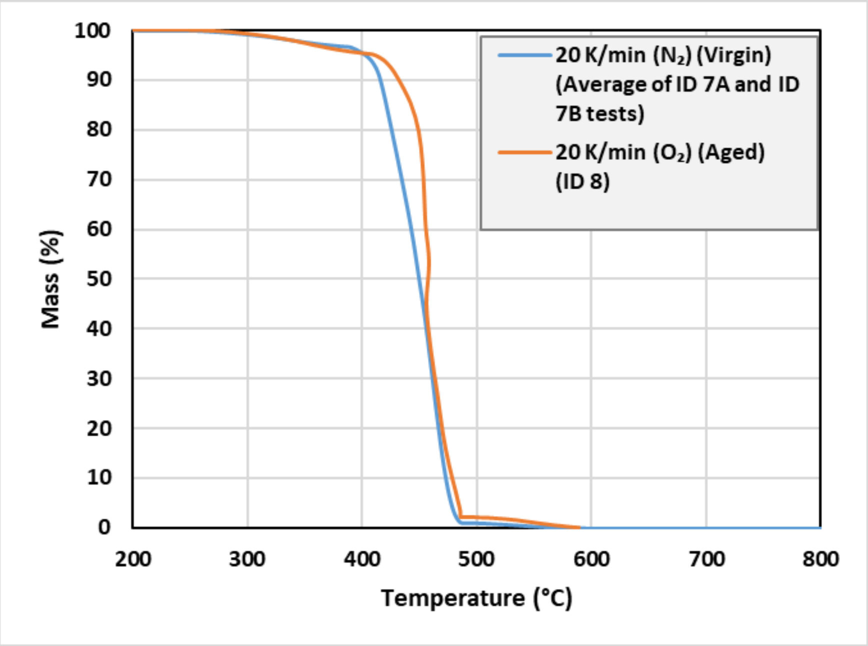


Figure 16. TGA result of mass loss of virgin XLPE sample and fast-aged XLPE sample at heating rate of 20 K/min in oxygen.

It can be noted from Figure 13 to Figure 16 that the thermal degradation of virgin XLPE sample and fast-aged XLPE sample approximately starts at around same temperature in oxygen. However, the virgin XLPE sample shows steeper mass loss rate after the initiation of degradation.

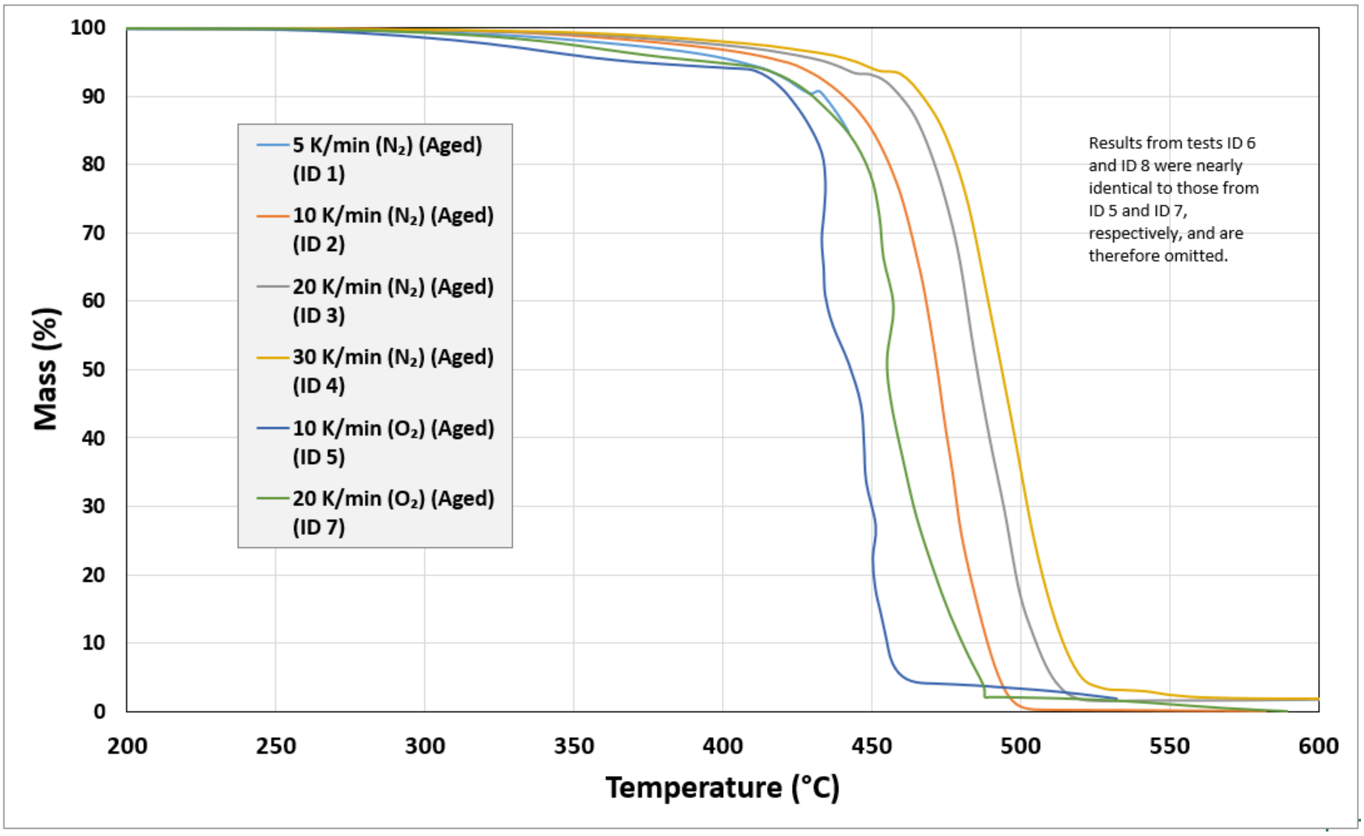


Figure 17. TGA result of mass loss of fast-aged XLPE sample all together at different heating rates in nitrogen and oxygen.

From Figure 17 it can be noted that the TGA results also collectively demonstrate that fast-aged XLPE follows a consistent thermal degradation pattern across a range of heating rates and atmospheric conditions. Regardless of test parameters, the polymer maintains its mass stability up to approximately 375–425°C, after which it undergoes rapid decomposition. The influence of heating rate is clearly visible: higher heating rates shift the apparent onset of decomposition to higher temperatures. Such behaviour aligns with general kinetic principles, where faster heating delays the apparent initiation of degradation and compresses the decomposition process into a narrower temperature window. In contrast, lower heating rates allow more time for early-stage breakdown, resulting in slightly earlier onset temperatures and more gradual mass loss. Atmosphere also plays a notable role. Under oxygen, degradation progresses somewhat earlier compared to nitrogen, reflecting the oxidative sensitivity of XLPE. The presence of oxygen accelerates possibly the chain scission and promotes a more aggressive mass-loss profile, especially in the initial stages. However, both nitrogen and oxygen conditions ultimately converge to nearly complete volatilization with minimal residue, indicating that fast-aged XLPE also exhibits low char-forming capability and is thermally less robust in terms of carbonaceous residue formation.

Overall, the results demonstrate that (fast) ageing primarily influences the start and early rate of degradation primarily in nitrogen environment.

3. Cone calorimeter experimental data of the XLPE sheets

The pyrolysis and burning behaviour of the XLPE material produced as described in Appendix A (Fabrication of the XLPE sheets) was also studied using Cone Calorimeter. Such behaviour was studied for both virgin sample and aged sample. For the study, here also same aged XLPE sheets which were slow-aged and fast-aged for TGA were used. Elaborate experimental plan was designed as shown in the Table 3 (Test plan A), Table 4 (Test plan B) and Table 5 (Test plan C). The cone calorimeter measurements were done in Aalto University using commercial cone calorimeter manufactured by Concept Equipment Ltd. Table 3 shows the test plan A which covers samples to be tested in cone calorimeter in air with spark. Table 4 shows the test plan B which covers samples to be tested in cone calorimeter in air without spark. Table 5 shows the test plan C which covers samples to be tested in cone calorimeter in nitrogen.

Table 3. Test plan A: Samples tested in cone calorimeter in air with spark.

Test ID	Virgin/Slow-aged/Fast-aged	Heat Flux (KW/m²)	Chamber Gas	Spark	Remark (If any)
ID1_V_Air	Virgin	**25**	Air	Yes	
ID2_V_Air	Virgin	**25**	Air	Yes	repetition
ID3_V_Air	Virgin	**25**	Air	Yes	repetition
ID4_V_Air	Virgin	**35**	Air	Yes	
ID5_V_Air	Virgin	**35**	Air	Yes	repetition
ID6_V_Air	Virgin	**35**	Air	Yes	repetition
ID7_V_Air	Virgin	**50**	Air	Yes	
ID8_V_Air	Virgin	**50**	Air	Yes	repetition
ID9_V_Air	Virgin	**50**	Air	Yes	repetition
ID1_SA_Air	Slow-aged	**25**	Air	Yes	
ID2_SA_Air	Slow-aged	**25**	Air	Yes	repetition
ID3_SA_Air	Slow-aged	**35**	Air	Yes	
ID4_SA_Air	Slow-aged	**35**	Air	Yes	repetition
ID5_SA_Air	Slow-aged	**50**	Air	Yes	
ID6_SA_Air	Slow-aged	**50**	Air	Yes	repetition, test failed
ID1_FA_Air	Fast-aged	**25**	Air	Yes	
ID2_FA_Air	Fast-aged	**25**	Air	Yes	
ID3_FA_Air	Fast-aged	**35**	Air	Yes	
					V: Virgin; SA: Slow-aged; FA: Fast-aged

Table 4. Test plan B: Samples tested in cone calorimeter in air without spark.

Test ID	Virgin/Slow-aged/Fast-aged	Heat Flux (KW/m²)	Chamber Gas	Spark	Remark (If any)
ID1_V_Air_NS	Virgin	**25**	Air	No	
ID2_V_Air_NS	Virgin	**35**	Air	No	
ID1_SA_Air_NS	Slow-aged	**25**	Air	No	
ID2_SA_Air_NS	Slow-aged	**35**	Air	No	
					V: Virgin; SA: Slow-aged; NS: No Spark

Table 5. Test plan C: Samples tested in cone calorimeter in nitrogen.

Test ID	Virgin/Slow-aged/Fast-aged	Heat Flux (KW/m²)	Chamber Gas	Spark	Remark (If any)
ID1_V_N_2	Virgin	**25**	Nitrogen	NA	
ID2_V_N_2	Virgin	**25**	Nitrogen	NA	repetition
ID3_V_N_2	Virgin	**35**	Nitrogen	NA	
ID4_V_N_2	Virgin	**35**	Nitrogen	NA	repetition
ID1_SA_N_2	Slow-aged	**25**	Nitrogen	NA	
ID2_SA_N_2	Slow-aged	**25**	Nitrogen	NA	repetition
ID1_FA_N_2	Fast-aged	**25**	Nitrogen	NA	
ID2_FA_N_2	Fast-aged	**35**	Nitrogen	NA	
					V: Virgin; SA: Slow-aged; FA: Fast-aged

The detailed analysis in this work is centered on Test Plan A (air with spark) because such configuration most closely represents the conditions under which XLPE insulation is expected to behave during real fire scenarios. In practical fire environments, materials are exposed to oxygen-rich atmospheres and typically encounter external ignition sources such as flames, electrical arcs, or hot surfaces. Test Plan A reflects such combination of factors and therefore provides the most directly applicable data for assessing the burning behaviour, heat release, and mass-loss characteristics of XLPE under realistic fire conditions. These parameters are also the most relevant for engineering fire-safety assessments and for generating inputs required in computational fire modelling frameworks. The fast-aged XLPE samples were excluded from the Test Plan A analysis because the high-temperature aging procedure (220 °C for four hours) caused substantial thermal and chemical alteration of the material—far beyond what XLPE can experiences during normal long-term service aging in nuclear power plant environments. Although excluded from the main analysis, such samples may still hold value for specialised future studies involving extreme pre-heating scenarios, but they are not suitable for the primary fire-performance assessment conducted under Test Plan A.

Although Test Plans B and C are not analysed in detail in the present work, their results hold significant value for future research.

- Test Plan B (air without spark) provides insight into *self-ignition behaviour*, helping determine whether XLPE can ignite without an imposed ignition source. This information is useful in scenarios where the onset of flaming may be delayed or where ignition sources are uncertain.
- Test Plan C (nitrogen atmosphere) isolates the *pure pyrolysis behaviour* of XLPE by eliminating oxidation and flaming. Such data are essential for developing advanced material-reaction models, improving the accuracy of CFD simulations, and supporting deeper investigations into thermal decomposition mechanisms.

By prioritizing Test Plan A for full analysis while preserving Plans B and C for targeted research applications, the study maintains a clear focus on realistic fire-performance evaluation while ensuring that broader scientific and modelling needs can be pursued in future work.

Appendix D contains all results of Test plan A altogether. Appendix E contains all results of Test plan B. Appendix F contains all results of Test plan C.

3.1 Cone Calorimeter Results for Test Plan A

HRRPUA in the following figures and text stands for heat release per unit area. The graph scales have been kept consistent to enable clear visual comparison.

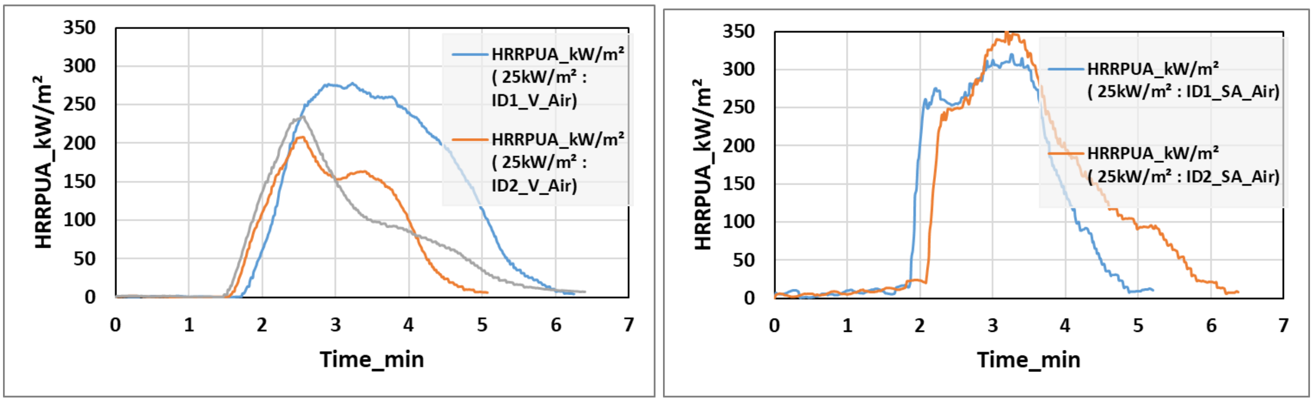


Figure 18. Left figure: HRRPUA for virgin samples in air under 25kW/m² radiative heat flux; Right figure: HRRPUA for slow-aged samples in air under 25kW/m² radiative heat flux.

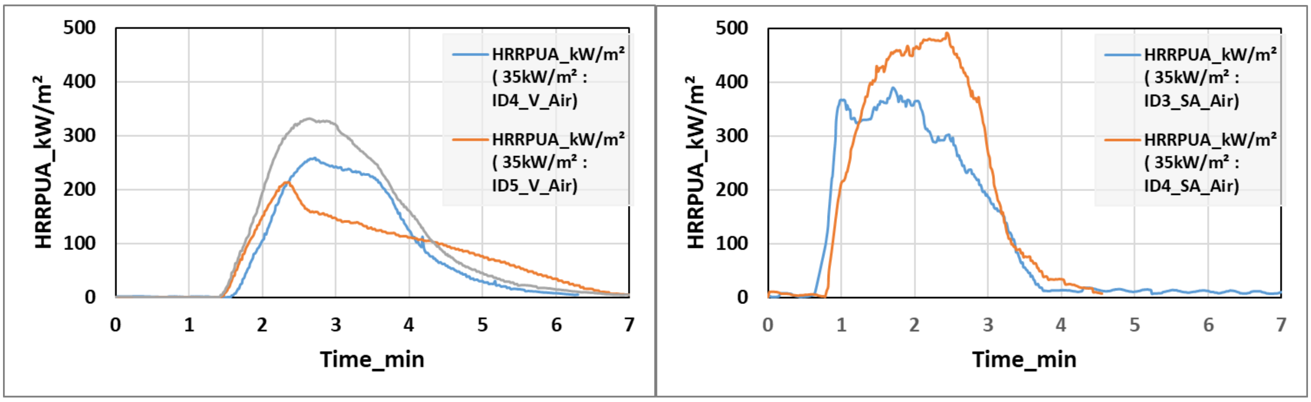


Figure 19. Left figure: HRRPUA for virgin samples in air under 35kW/m² radiative heat flux; Right figure: HRRPUA for slow-aged samples in air under 35kW/m² radiative heat flux.

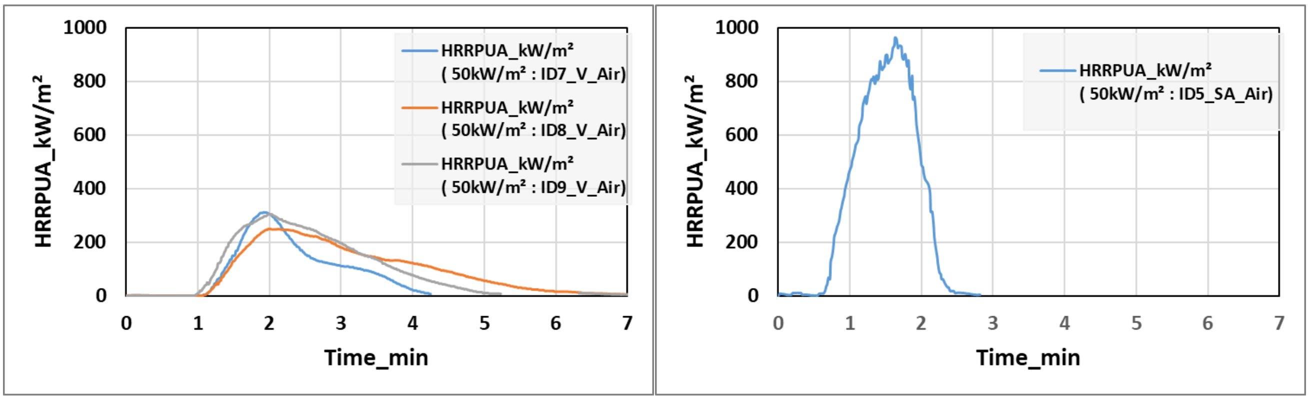


Figure 20. Left figure: HRRPUA for virgin samples in air under 50kW/m² radiative heat flux; Right figure: HRRPUA for slow-aged samples in air under 50kW/m² radiative heat flux.

Across all three radiative heat flux levels (25, 35, and 50 kW/m²), the slow-aged (SA) XLPE samples consistently exhibit higher peak HRRPUA values compared to the corresponding virgin samples, indicating that aging enhances the intensity of the initial flaming phase. At 25 kW/m², although the burning duration of the SA samples is shorter, their peak heat release rate still surpasses that of the virgin curves, reflecting a sharper combustion response once ignition occurs. Such trend becomes more pronounced at 35 kW/m², where the SA samples not only ignite slightly earlier but also reach higher peaks with a steeper rise, followed by a faster decline, suggesting that aging promotes more volatile-rich or more reactive decomposition products. At 50 kW/m², the contrast is strongest: the SA sample shows a very high and narrow peak, far exceeding the broader and lower peak profiles of the virgin samples, indicating highly concentrated heat release over a short duration. Despite these differences in magnitude and burn dynamics, the flameout time of the SA samples is generally shorter, while virgin samples show longer burn tails and lower peak intensities. Overall, the graphs demonstrate that slow aging shifts the combustion behaviour of XLPE toward higher peak intensity but shorter duration flaming, with the SA peaks consistently exceeding those of virgin material at all tested heat fluxes.

4. Discussion and Conclusion

This work presents an experimental investigation of the thermal degradation and fire behaviour of cross-linked polyethylene (XLPE), covering both virgin material and artificially aged counterparts. By combining micro-scale TGA/DSC experiments with bench-scale cone calorimeter testing on XLPE sheets manufactured from the same base material, the study provides a consistent multi-scale dataset suitable for fire-safety analysis and modelling. The work was carried out within Task 2.2 of the FASAANI project under the SAFER2028 programme and directly builds on experimental needs identified in the earlier SAFIR2022-URAN project, particularly the requirement for detailed degradation data to support CFD-based fire simulations.

The TGA/DSC results show that slow thermal aging at moderate temperature (140 °C) primarily affects the onset and early kinetics of degradation, rather than fundamentally altering the decomposition pathway. In nitrogen, slow-aged XLPE begins to degrade at slightly lower temperatures than virgin material, whereas virgin XLPE exhibits higher mass-loss rates once degradation has initiated. In oxygen, both materials show similar degradation onset temperatures, but the aged XLPE displays a steeper initial mass-loss rate, indicating enhanced oxidative sensitivity. Across all heating rates and atmospheres, XLPE exhibits minimal char formation, confirming its low residue yield and limited thermal robustness. These findings indicate that aging modifies degradation kinetics rather than the overall degradation mechanism.

Fast-aged XLPE samples produced at high temperature (220 °C for four hours) were observed to undergo substantial physical and chemical changes, suggesting partial thermal decomposition during the aging process. As such conditions exceed those experienced during normal long-term service in nuclear power plants, fast-aged samples were excluded from the primary fire-performance assessment. Nevertheless, they remain relevant for specialised scenarios involving extreme thermal pre-heating prior to ignition and exploratory studies related to flame-spread behaviour.

Cone calorimeter experiments were conducted under three configurations to capture different aspects of XLPE fire behaviour. The detailed analysis focused on Test Plan A (air with spark), which best represents realistic fire conditions with oxygen availability and external ignition sources. Under these conditions, slow-aged XLPE consistently exhibited higher peak heat release rates per unit area than virgin XLPE at all tested heat fluxes (25, 35, and 50 kW/m²), together with a steeper rise to peak HRR and a shorter burning duration. This indicates that slow aging shifts XLPE combustion behaviour toward more intense but shorter-lived flaming, whereas virgin XLPE shows lower peak intensities and longer burn tails.

Although Test Plans B (air without spark) and C (nitrogen atmosphere) were not analysed in detail, they provide valuable complementary datasets for future research, supporting assessment of self-ignition behaviour and pure pyrolysis behaviour without flame feedback. Together, the TGA/DSC and cone calorimeter results presented in this report are not only intended for computational material modelling but are generally applicable wherever detailed information on base XLPE thermal degradation is required for studies and modelling. It should be noted, however, that the present results apply to the specific XLPE material studied. Different XLPE grades and formulations, particularly variations in antioxidant type and content, may exhibit different aging and degradation behaviour. Furthermore, interpretation of aging effects in oxygen must be made with care, as oxygen diffusion into XLPE is very limited and, in the present experiments, oxidation primarily affects the sample surface, which does not fully replicate the real in-service condition where oxygen ingress occurs over long timescales. Nevertheless, the present results characterise the fire behaviour of unmodified (base) XLPE and therefore provide a robust reference baseline for comparison and for guiding future studies on aged and formulation-modified XLPE materials

Overall, the results indicate that thermal aging influences the fire behaviour of unmodified (base) XLPE, particularly by increasing peak heat release under flaming conditions while reducing burn duration. The provided experimental dataset can be further used for the development and validation of computational material models for the base XLPE material used in cable insulation. Such models are needed for the fire-safety assessment of long-term-used XLPE-based cables in nuclear power plants.

References

Helminen, K., Korhonen, T., Kankaanpää, J. (2024), TGA and DSC test results of XLPE virgin and fast-aged samples. Research Report VTT-R-00703-24, VTT Technical Research Centre of Finland, Espoo, Finland. 30 p.

Korhonen, T., Verma, N. (2023). Effect of ageing on burning properties and fire spread of XLPE cables. Research Report VTT-R-01026-22, VTT Technical Research Centre of Finland, Espoo, Finland. 34 p.

Appendix A: Fabrication of the XLPE sheets

The process of preparing thin crosslinked XLPE sample sheets was carried out using a hot press technique to induce crosslinking in the XLPE granules and produce solid, crosslinked sheets for further testing. A small amount of granules (~30 g) was carefully measured and poured onto the surface of a pre-heated hot-pressing plate, which was heated to 160°C, slightly above the materials melting point. At this temperature, the polymer granules were melted uniformly over the span of 10 minutes. After the initial melting phase, pressure was applied to the molten XLPE to ensure uniform thickness and distribution of the sheet. Following this the temperature of the hot press plate was raised to 210°C to induce crosslinking. At this elevated temperature, the polymer chains began to form crosslinked bonds. This crosslinking phase was brief (~10 min) to prevent overexposure to heat, which could affect the sample's integrity. Once crosslinking was achieved, the sample was slowly cooled to allow for controlled solidification.

The degree of crosslinking in the hot pressed XLPE sample sheets was assessed using the Soxhlet extraction method. This technique allows for the separation of the non-crosslinked polymer fraction from the crosslinked gel by utilizing a solvent, such as xylene, which selectively dissolves the non-crosslinked polymer chains. The residual gel, which remains unaffected by the solvent, represents the crosslinked portion of the polymer. The Soxhlet extraction process is therefore an effective tool for quantifying the degree of crosslinking in crosslinked polyethylene materials.

In this work, xylene was chosen as the solvent for its ability to dissolve the non-crosslinked portions of the polymer while leaving the crosslinked gel intact. The entire procedure was performed inside a fume cupboard to prevent exposure to xylene vapours. The Soxhlet apparatus used for the extraction consisted of a boiling flask, a condenser, and an extraction chamber. A metal mesh was placed in the extraction chamber to hold the XLPE sample in place. The sample was carefully weighed before and after the extraction to calculate the mass of the remaining gel and determine the degree of crosslinking.

The process began by preparing a small sample of XLPE, which was placed in the metal mesh inside the Soxhlet extraction chamber, and an extraction sock. Xylene was then poured into the boiling flask of the Soxhlet apparatus. The xylene was heated to its boiling point (~138.5°C), causing it to vaporize and rise into the condenser. The vapor then condensed and dripped down onto the XLPE sample inside the extraction sock. This reflux cycle allowed the xylene to continuously wash over the sample, selectively dissolving the non-crosslinked polymer chains. This extraction was carried out for 8 hours to ensure thorough dissolution of the soluble polymer fraction. After the extraction period the remaining sample was removed from the Soxhlet apparatus, left to dry and then its final mass was measured.

To determine the degree of crosslinking in the XLPE sample, the initial and final masses of the sample were compared. The initial mass represented the total polymer content, while the final mass displays the crosslinked portion of the polymer, which had not dissolved in the xylene. The difference between the two masses indicates the amount of non-crosslinked material that had been dissolved and removed during the Soxhlet extraction.

The degree of crosslinking was calculated using the following equation:

$$Gel\,fraction(\%) = \frac{Mass\ of\ residual\ gel}{Initial\ mass\ of\ sample} \cdot 100$$

For the XLPE sample to be considered adequately crosslinked, the gel fraction needed to be greater than 50%. The results of the analysis indicated that all XLPE sheets tested were well crosslinked, as shown in Table 2.

Table 6. XLPE sheets fabricated. The prepared sheets were cut into 11x11 cm^2.

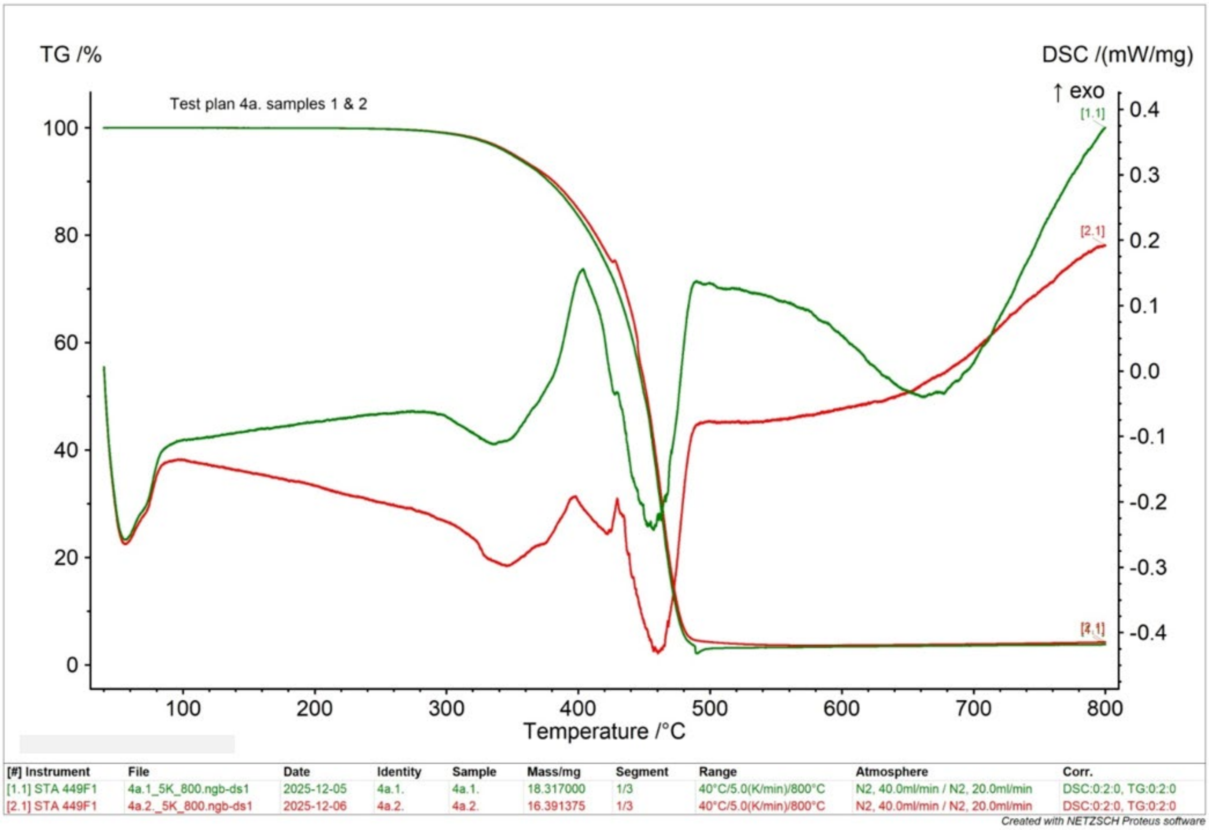
Sample	Pieces	Piece height average (mm)	Piece width average (mm)	Piece thickness average (mm)	Degree of cross linkage average(%)
Sheet 1	9	115	113,4	1,61	89,15
Sheet 2	11	116,3	114,3	1,68	93,02
Sheet 3	6	115,6	113,2	1,55	73,67
Sheet 4	7	115,9	114,1	1,63	85,23

Appendix B: TGA/DSC results of Slow-aged XLPE samples

Table 1 is put here for quick reference for the test results.

Table 1. The experimental TGA/DSC campaign for the slow-aged XLPE.

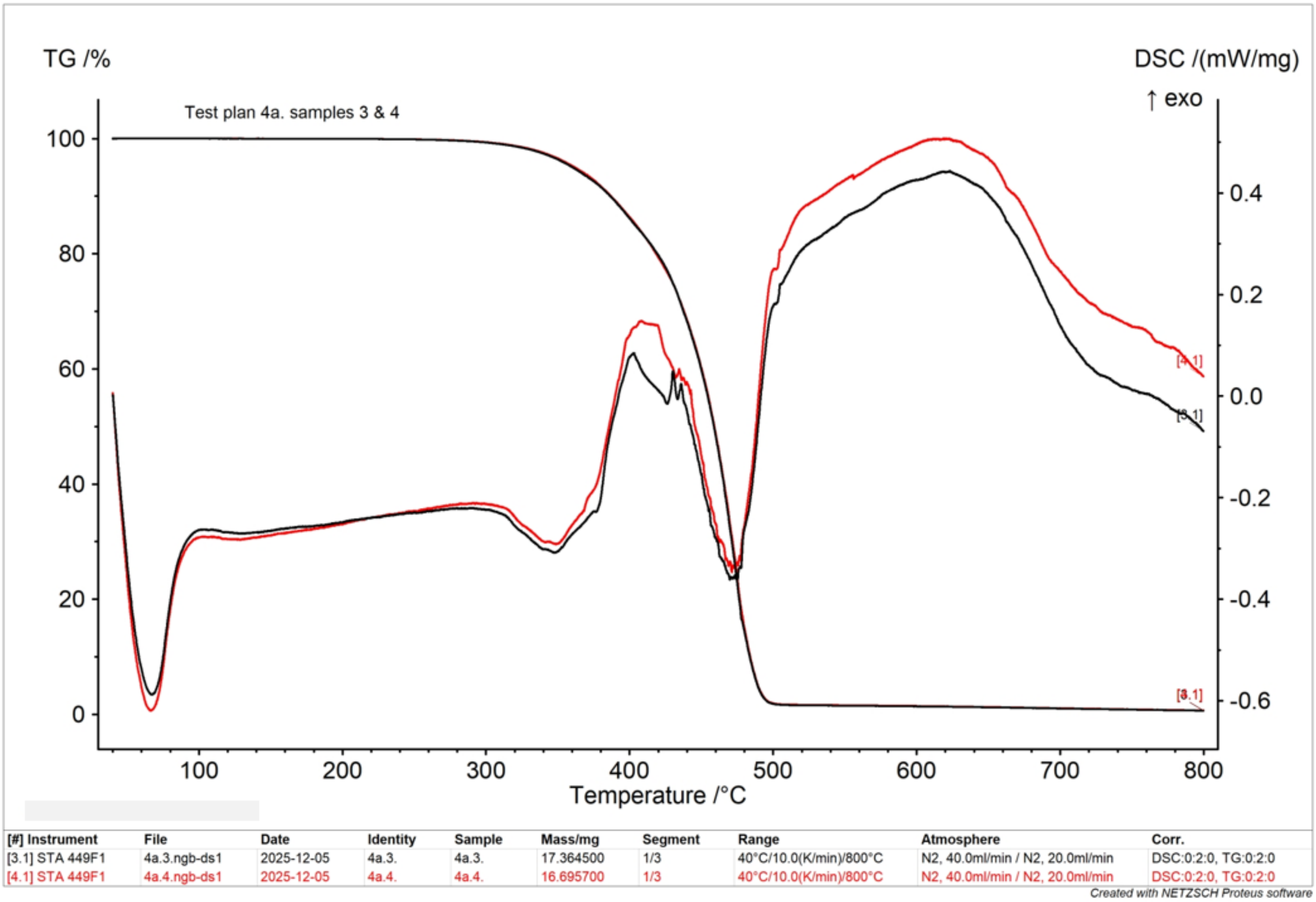
ID	Atmosphere	Heating Rate (K/min)
1	N_2	5
2	N_2	5
3	N_2	10
4	N_2	10
5	N_2	20
6	N_2	20
7	N_2	30
8	N_2	30
9	O_2	10
10	O_2	10
11	O_2	20
12	O_2	20



[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[1.1] STA 449F1	4a.1_5K_800.ngb-ds1	2025-12-05	4a.1.	4a.1.	18.317000	1/3	40°C/5.0(K/min)/800°C	N2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0
[2.1] STA 449F1	4a.2._5K_800.ngb-ds1	2025-12-06	4a.2.	4a.2.	16.391375	1/3	40°C/5.0(K/min)/800°C	N2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0

Created with NETZSCH Proteus software

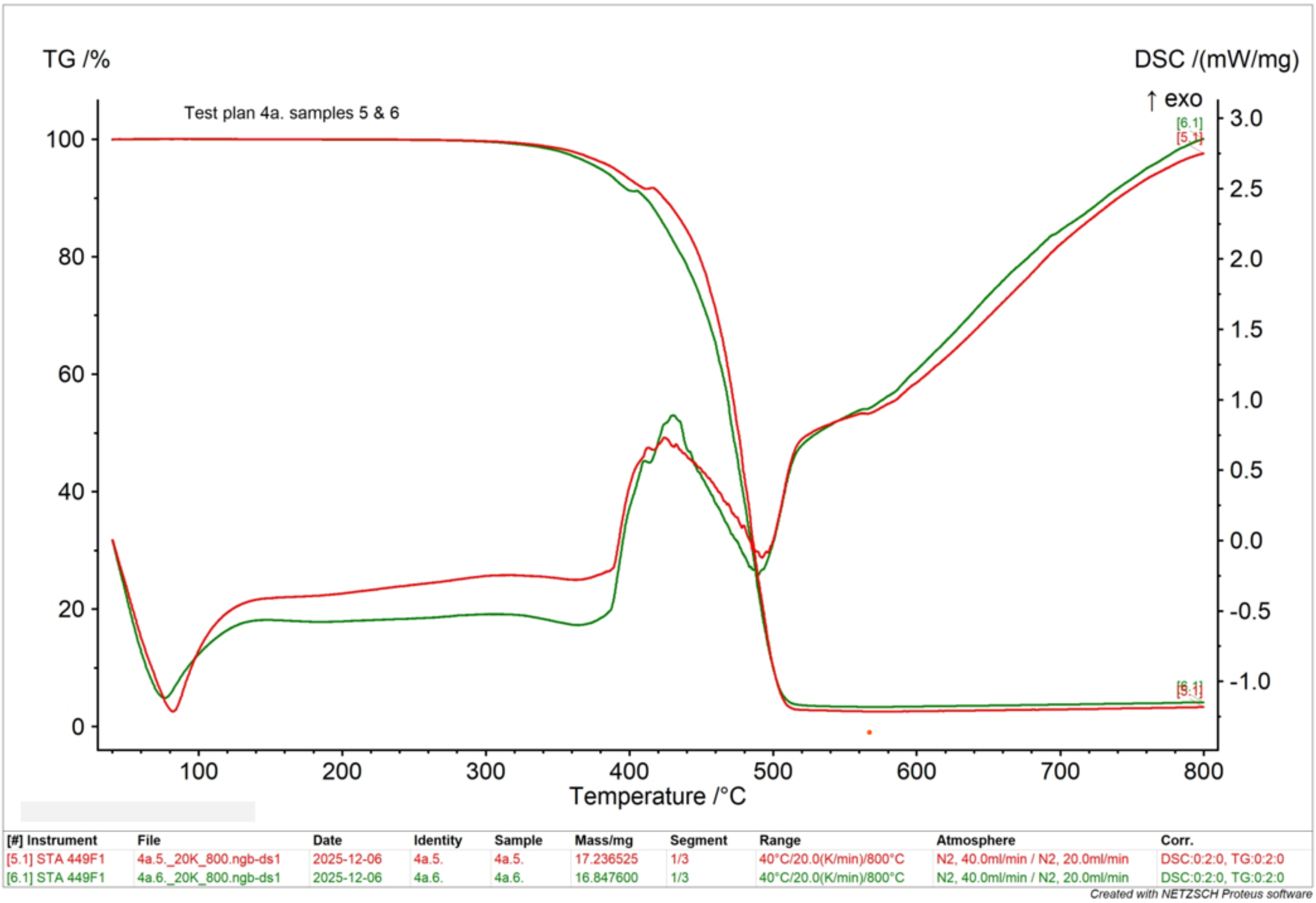
Figure 21. TGA/DSC results for test ID 1 (4a.1 in figure) and ID 2 (4a.2 in figure) for slow-aged XLPE samples.



[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[3.1] STA 449F1	4a.3.ngb-ds1	2025-12-05	4a.3.	4a.3.	17.364500	1/3	40°C/10.0(K/min)/800°C	N2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0
[4.1] STA 449F1	4a.4.ngb-ds1	2025-12-05	4a.4.	4a.4.	16.695700	1/3	40°C/10.0(K/min)/800°C	N2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0

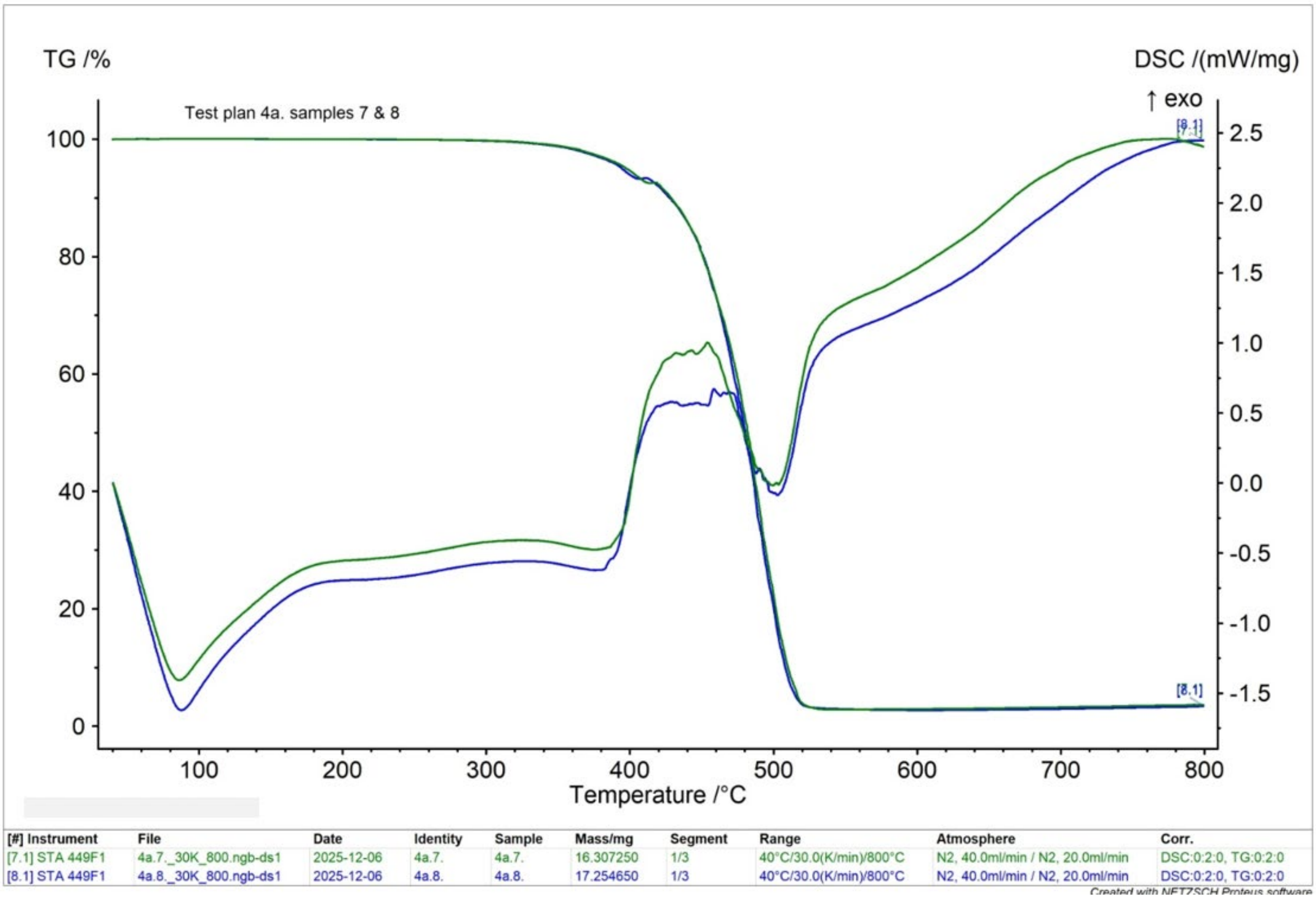
Created with NETZSCH Proteus software

Figure 22. TGA/DSC results for test ID 3 (4a.3 in figure) and ID 4 (4a.4 in figure) for slow-aged XLPE samples.



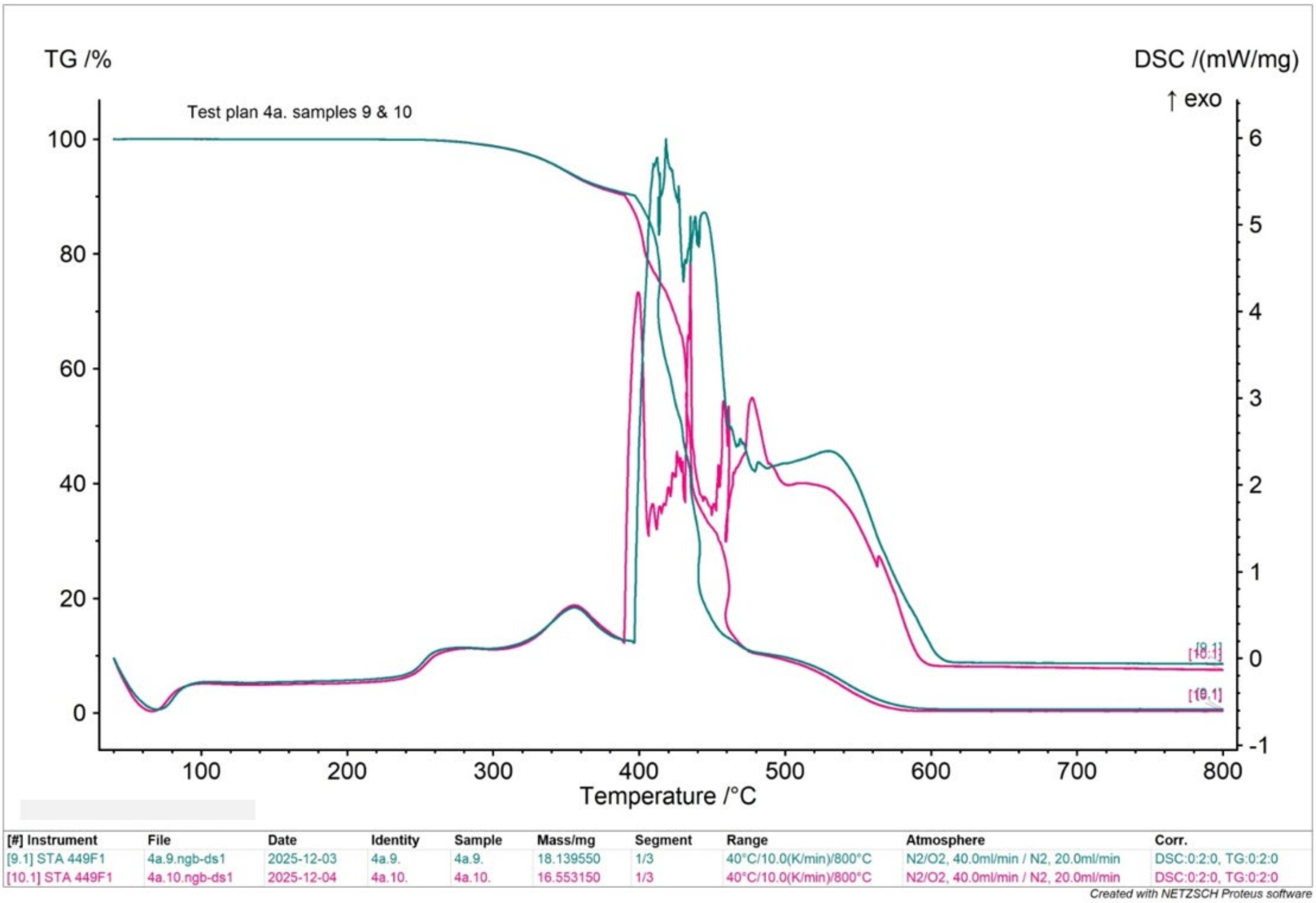
[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[5.1] STA 449F1	4a.5._20K_800.ngb-ds1	2025-12-06	4a.5.	4a.5.	17.236525	1/3	40°C/20.0(K/min)/800°C	N2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0
[6.1] STA 449F1	4a.6._20K_800.ngb-ds1	2025-12-06	4a.6.	4a.6.	16.847600	1/3	40°C/20.0(K/min)/800°C	N2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0

Figure 23. TGA/DSC results for test ID 5 (4a.5 in figure) and ID 6 (4a.6 in figure) for slow-aged XLPE samples.



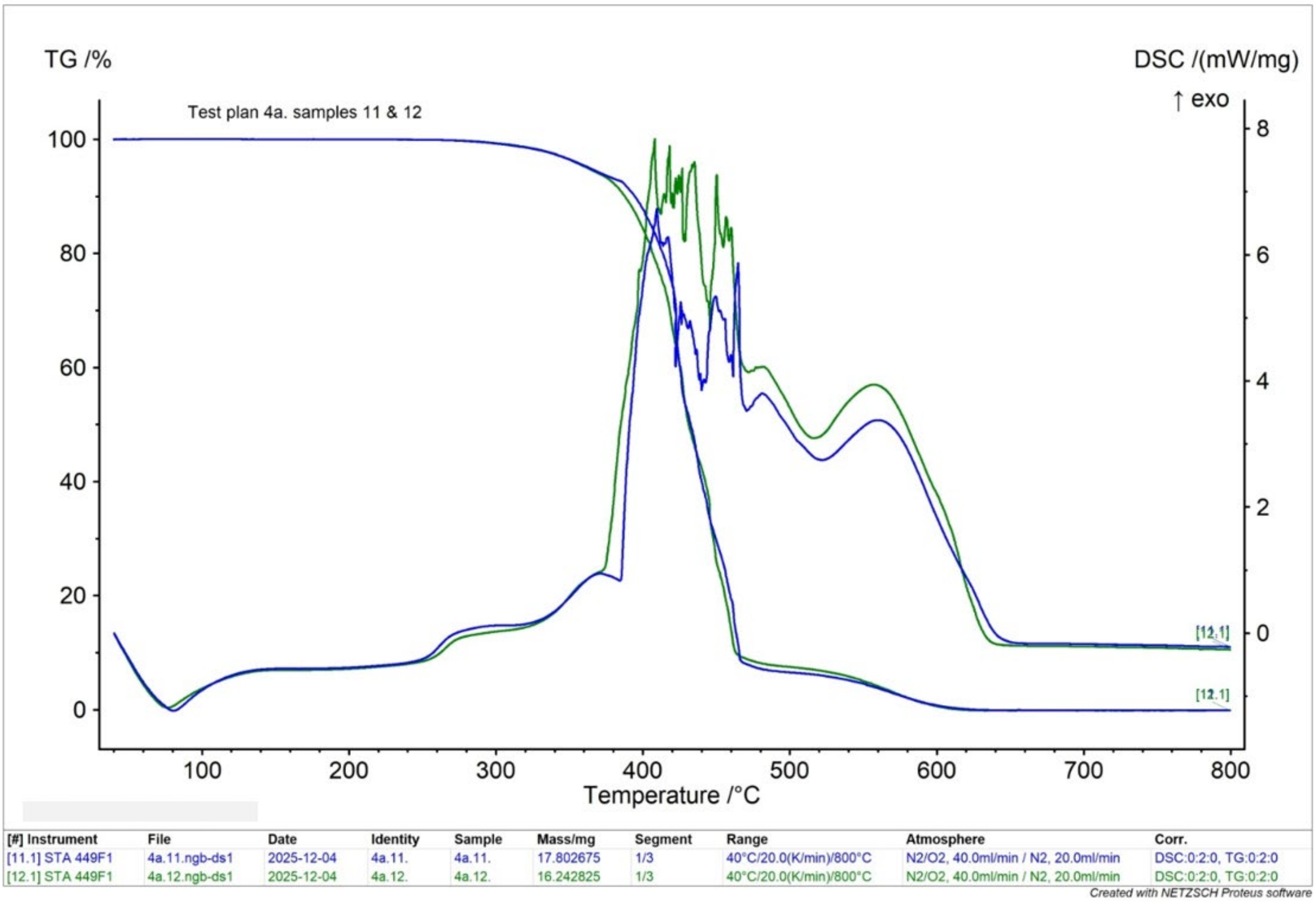
[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[7.1] STA 449F1	4a.7._30K_800.ngb-ds1	2025-12-06	4a.7.	4a.7.	16.307250	1/3	40°C/30.0(K/min)/800°C	N2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0
[8.1] STA 449F1	4a.8._30K_800.ngb-ds1	2025-12-06	4a.8.	4a.8.	17.254650	1/3	40°C/30.0(K/min)/800°C	N2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0

Figure 24. TGA/DSC results for test ID 7 (4a.7 in figure) and ID 8 (4a.8 in figure) for slow-aged XLPE samples.



[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[9.1] STA 449F1	4a.9.ngb-ds1	2025-12-03	4a.9.	4a.9.	18.139550	1/3	40°C/10.0(K/min)/800°C	N2/O2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0
[10.1] STA 449F1	4a.10.ngb-ds1	2025-12-04	4a.10.	4a.10.	16.553150	1/3	40°C/10.0(K/min)/800°C	N2/O2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0

Figure 25. TGA/DSC results for test ID 9 (4a.9 in figure) and ID 10 (4a.10 in figure) for slow-aged XLPE samples.



[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[11.1] STA 449F1	4a.11.ngb-ds1	2025-12-04	4a.11.	4a.11.	17.802675	1/3	40°C/20.0(K/min)/800°C	N2/O2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0
[12.1] STA 449F1	4a.12.ngb-ds1	2025-12-04	4a.12.	4a.12.	16.242825	1/3	40°C/20.0(K/min)/800°C	N2/O2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0

Figure 26. TGA/DSC results for test ID 11 (4a.11 in figure) and ID 12 (4a.12 in figure) for slow-aged XLPE samples.

Appendix C: TGA/DSC results of Fast-aged XLPE samples

Table 2 is put here for quick reference for the test results.

Table 2. The experimental TGA/DSC campaign for the fast-aged XLPE.

ID	Atmosphere	Heating Rate (K/min)
1	N_2	5
2	N_2	10
3	N_2	20
4	N_2	30
5	O_2	10
6	O_2	10
7	O_2	20
8	O_2	20

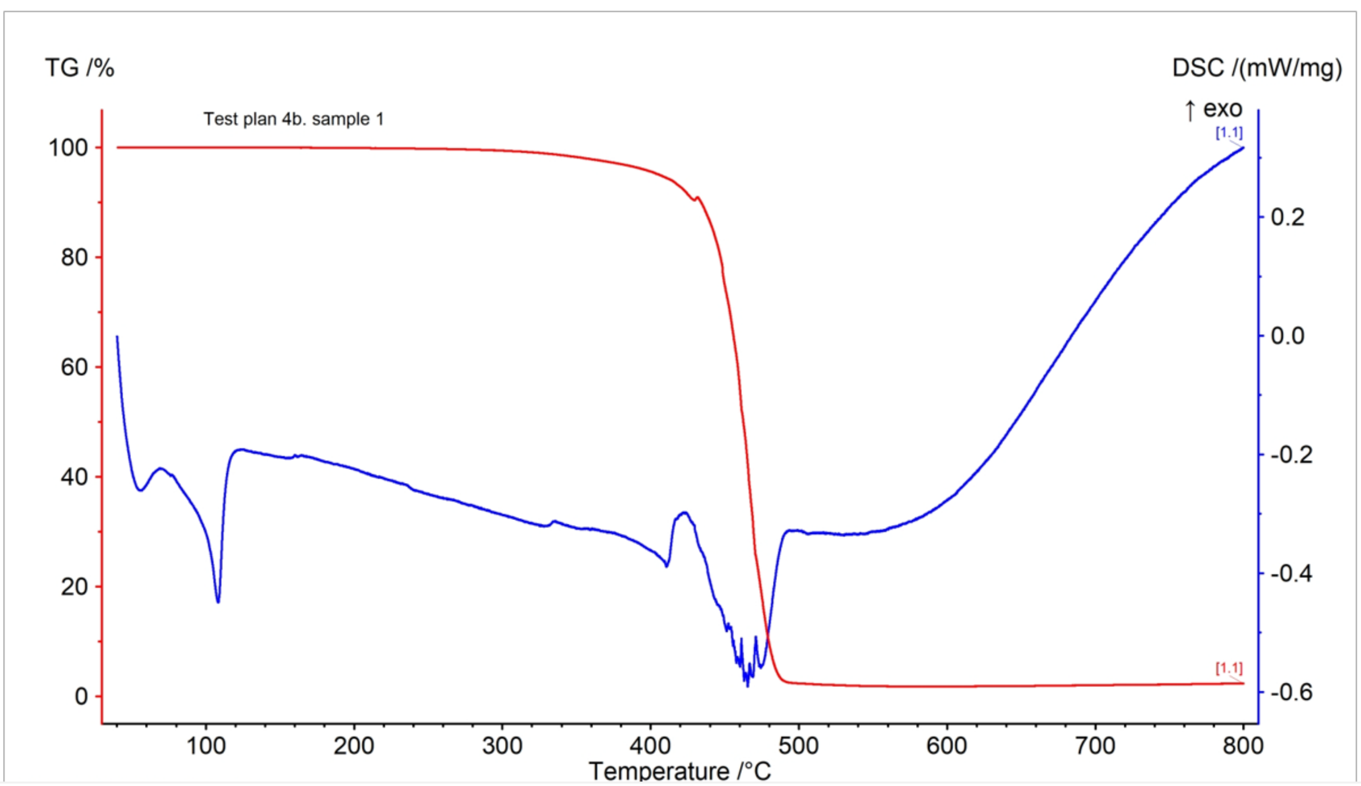


Figure 27. TGA/DSC results for test ID 1 (4b.1 in figure) for fast-aged XLPE samples.

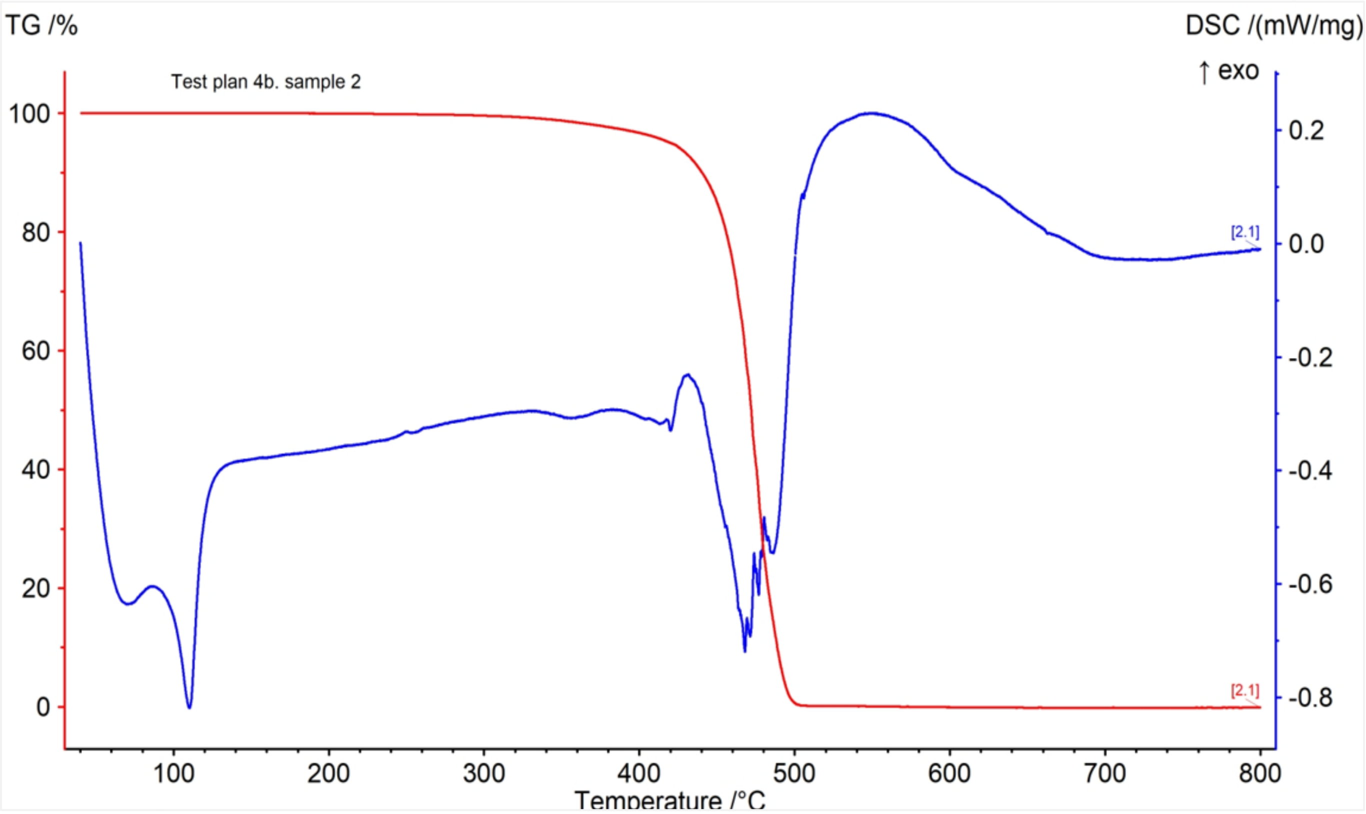


Figure 28. *TGA/DSC results for test ID 2 (4b.2 in figure) for fast-aged XLPE samples.*

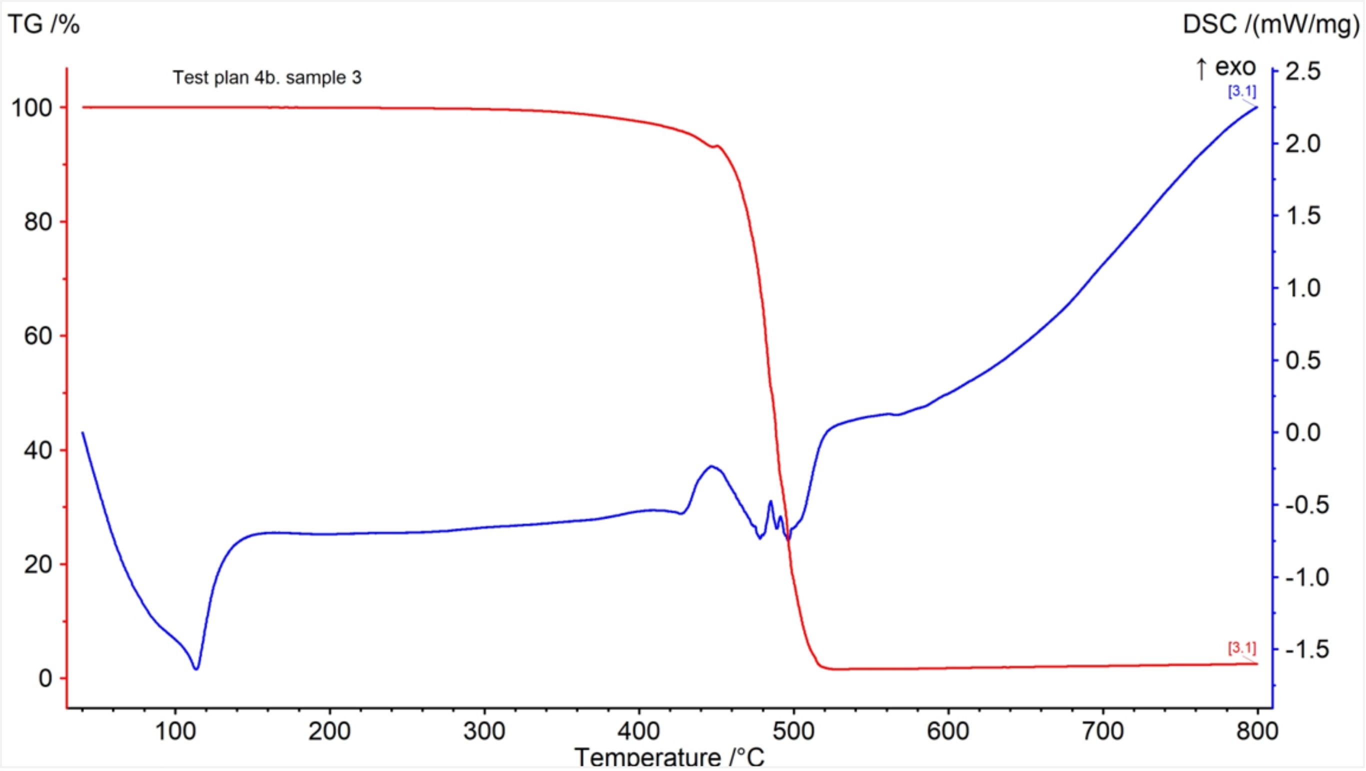


Figure 29. TGA/DSC results for test ID 3 (4b.3 in figure) for fast-aged XLPE samples.

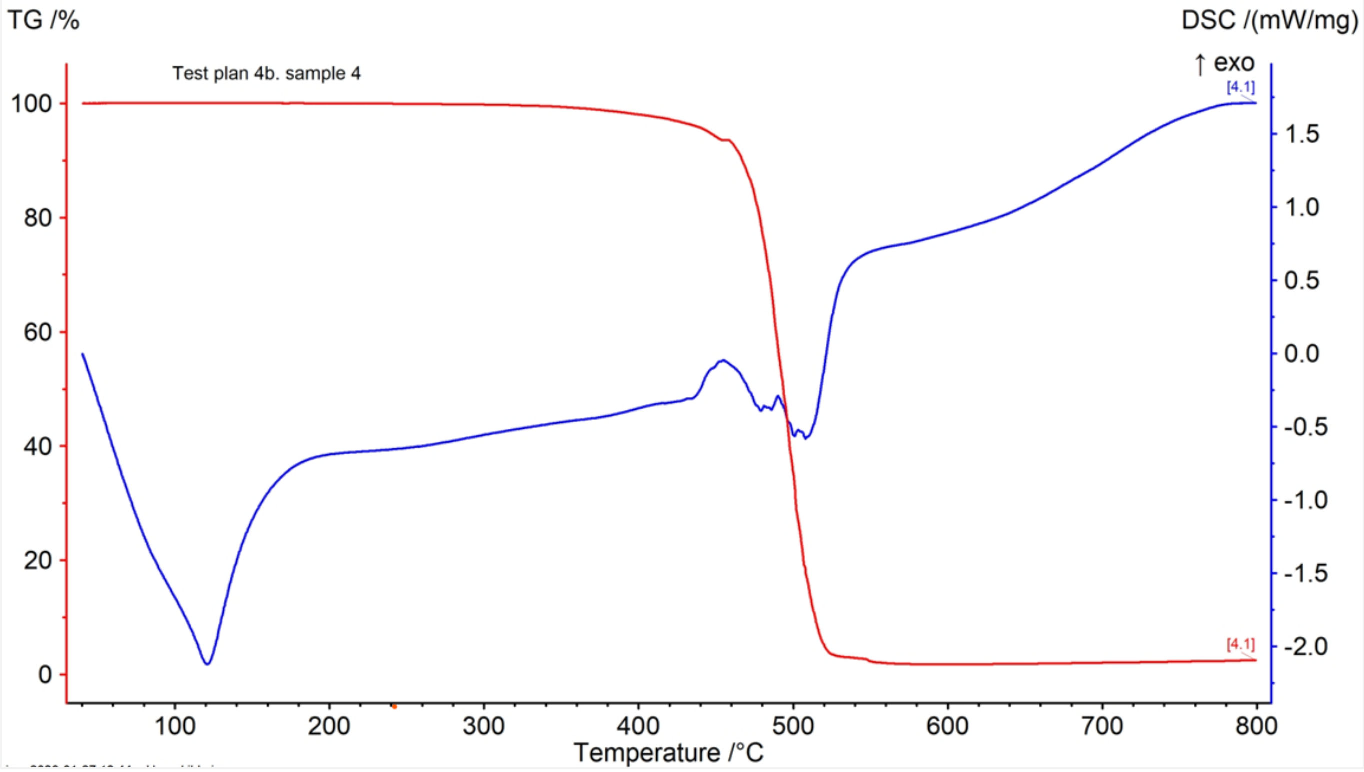
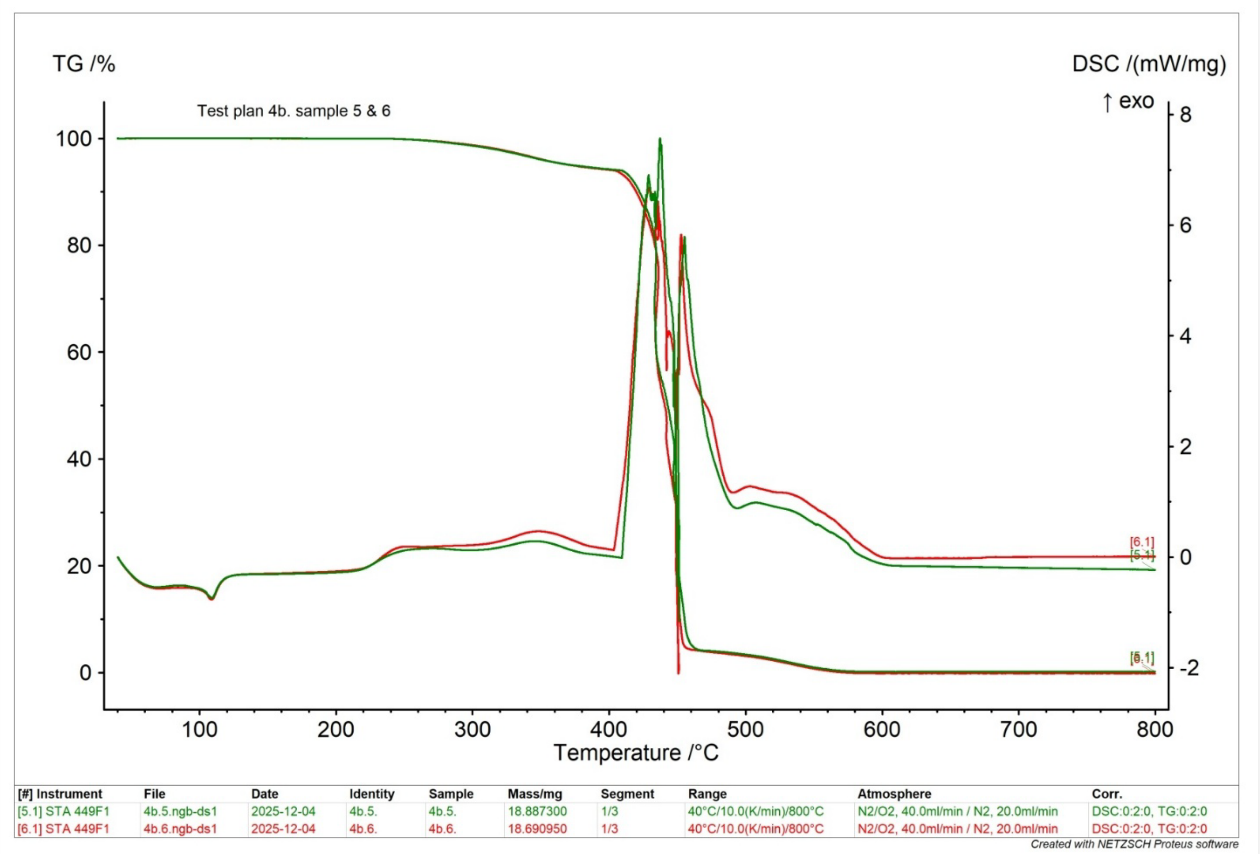
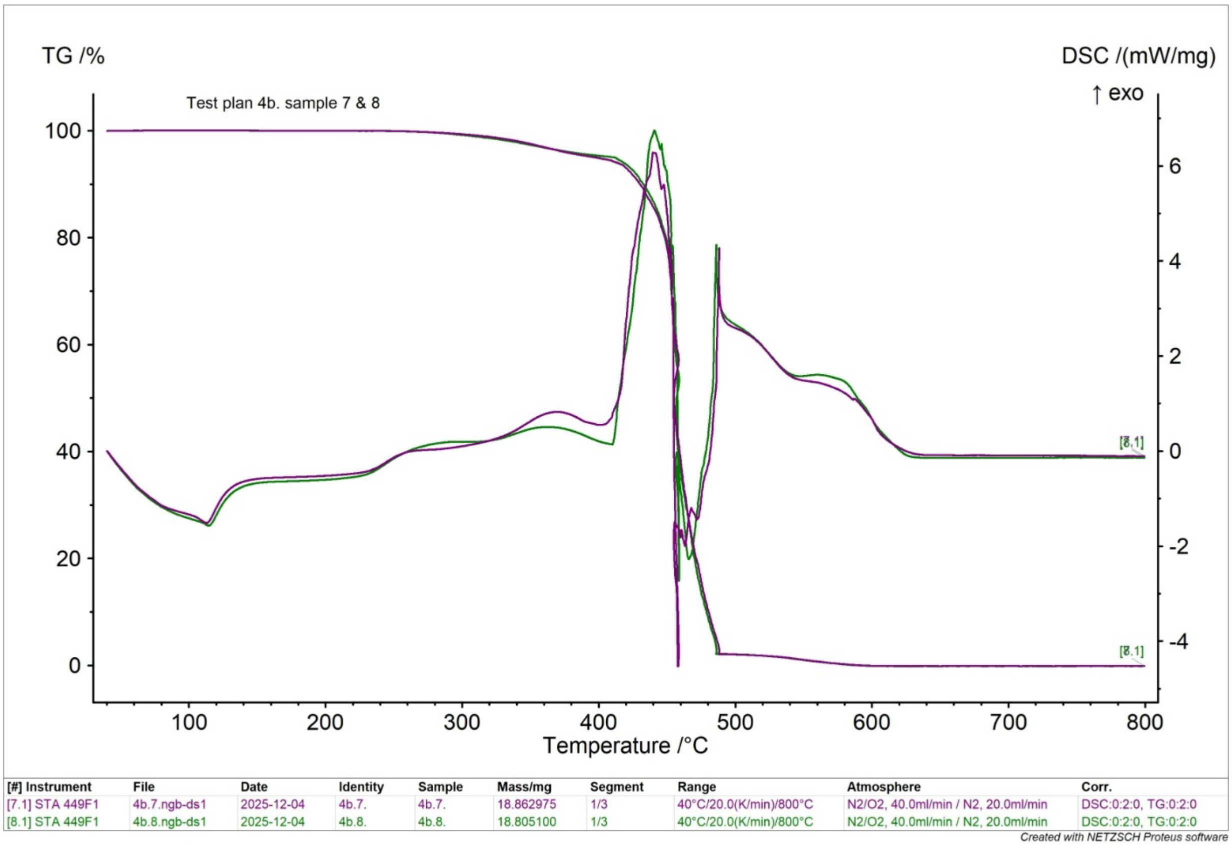


Figure 30. TGA/DSC results for test ID 4 (4b.4 in figure) for fast-aged XLPE samples.



[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[5.1] STA 449F1	4b.5.ngb-ds1	2025-12-04	4b.5.	4b.5.	18.887300	1/3	40°C/10.0(K/min)/800°C	N2/O2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0
[6.1] STA 449F1	4b.6.ngb-ds1	2025-12-04	4b.6.	4b.6.	18.690950	1/3	40°C/10.0(K/min)/800°C	N2/O2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0

Figure 31. TGA/DSC results for test ID 5 (4b.5 in figure) and ID 6 (4b.6 in figure) for fast-aged XLPE samples.



[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[7.1] STA 449F1	4b.7.ngb-ds1	2025-12-04	4b.7.	4b.7.	18.862975	1/3	40°C/20.0(K/min)/800°C	N2/O2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0
[8.1] STA 449F1	4b.8.ngb-ds1	2025-12-04	4b.8.	4b.8.	18.805100	1/3	40°C/20.0(K/min)/800°C	N2/O2, 40.0ml/min / N2, 20.0ml/min	DSC:0:2:0, TG:0:2:0

Created with NETZSCH Proteus software

Figure 32. TGA/DSC results for test ID 7 (4b.7 in figure) and ID 8 (4b.7 in figure) for fast-aged XLPE samples.

Appendix D: Heat Release Rate Per Unit Area (HRRPUA) and Mass loss rate (MLR) of all XLPE tested in cone calorimeter in air with spark

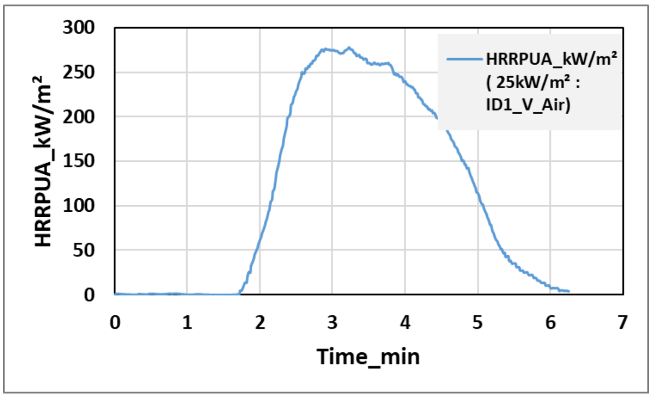
Table 3 is put here for quick reference for the test results.

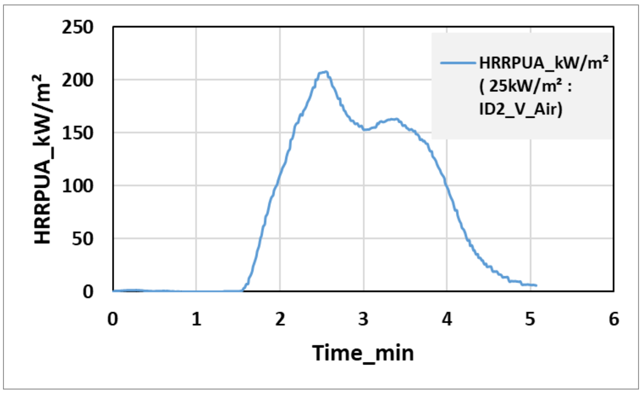
Table 3. Test plan A: Samples tested in cone calorimeter in air with spark.

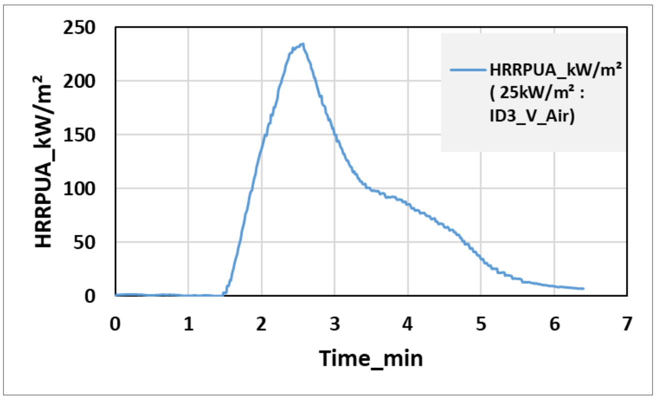
Test ID	Virgin/Slow-aged/Fast-aged	Heat Flux (KW/m²)	Chamber Gas	Spark	Remark (If any)
ID1_V_Air	Virgin	**25**	Air	Yes	
ID2_V_Air	Virgin	**25**	Air	Yes	repetition
ID3_V_Air	Virgin	**25**	Air	Yes	repetition
ID4_V_Air	Virgin	**35**	Air	Yes	
ID5_V_Air	Virgin	**35**	Air	Yes	repetition
ID6_V_Air	Virgin	**35**	Air	Yes	repetition
ID7_V_Air	Virgin	**50**	Air	Yes	
ID8_V_Air	Virgin	**50**	Air	Yes	repetition
ID9_V_Air	Virgin	**50**	Air	Yes	repetition
ID1_SA_Air	Slow-aged	**25**	Air	Yes	
ID2_SA_Air	Slow-aged	**25**	Air	Yes	repetition
ID3_SA_Air	Slow-aged	**35**	Air	Yes	
ID4_SA_Air	Slow-aged	**35**	Air	Yes	repetition
ID5_SA_Air	Slow-aged	**50**	Air	Yes	
ID6_SA_Air	Slow-aged	**50**	Air	Yes	repetition, test failed
ID1_FA_Air	Fast-aged	**25**	Air	Yes	
ID2_FA_Air	Fast-aged	**25**	Air	Yes	
ID3_FA_Air	Fast-aged	**35**	Air	Yes	

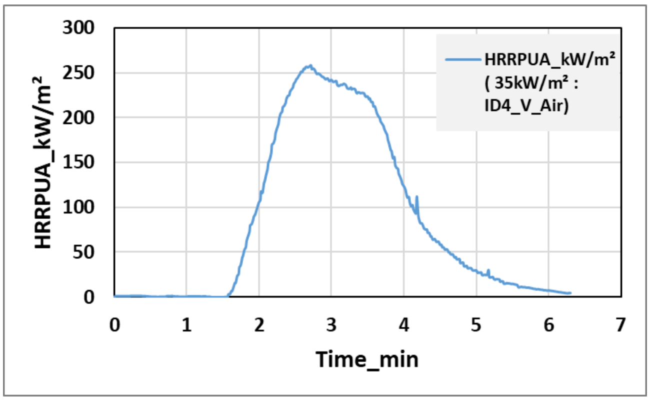
V: Virgin; SA: Slow-aged; FA: Fast-aged

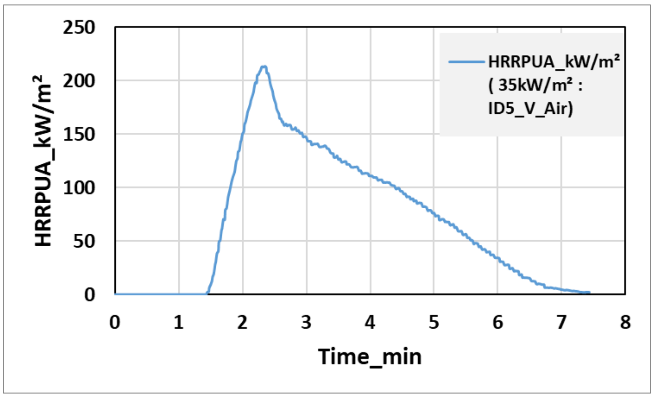
Charts of Heat Release Rate Per Unit Area (HRRPUA) of all XLPE samples tested in cone calorimeter in air with spark

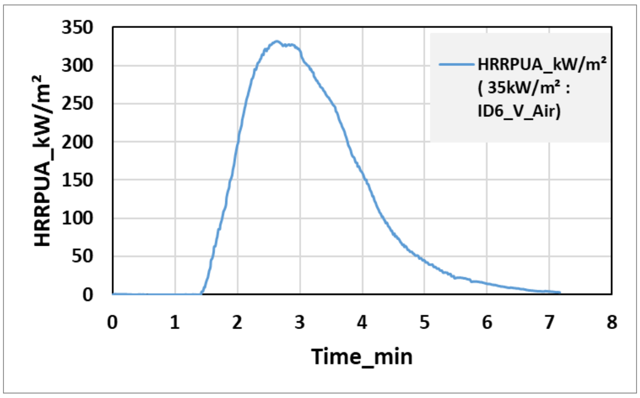


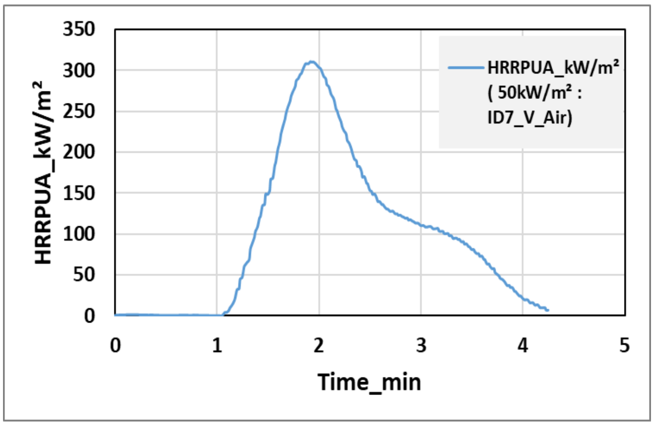


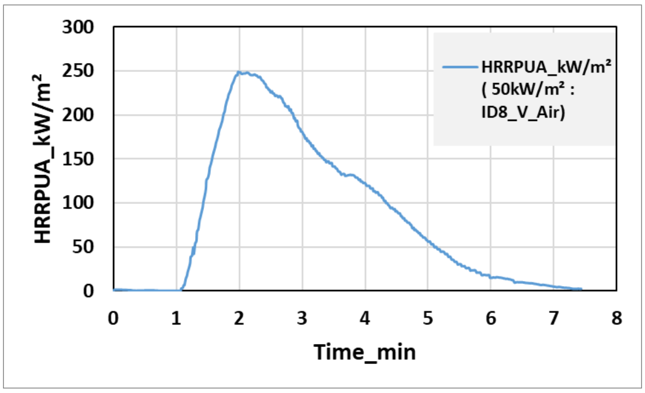

HRRPUA_kW/m²
250
200
150
100
50
0
0 1 2 3 4 5 6 7
Time_min
HRRPUA_kW/m² (25kW/m² : ID3_V_Air)

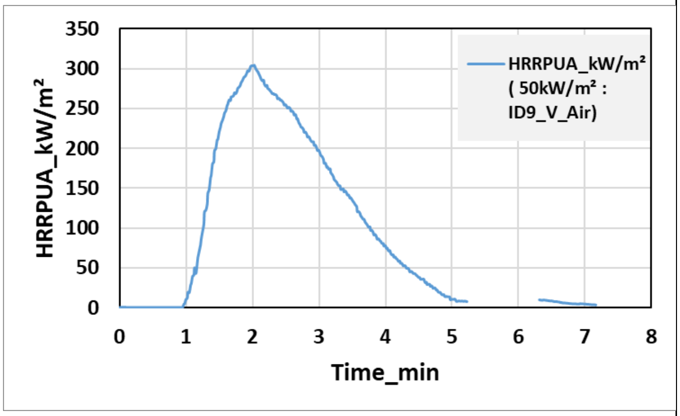

HRRPUA_kW/m²
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7
Time_min
HRRPUA_kW/m² (35kW/m² : ID4_V_Air)

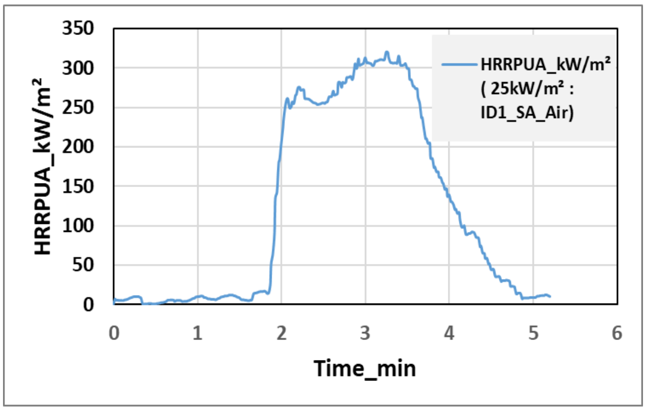

HRRPUA_kW/m²
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8
Time_min
HRRPUA_kW/m² (35kW/m² : ID5_V_Air)

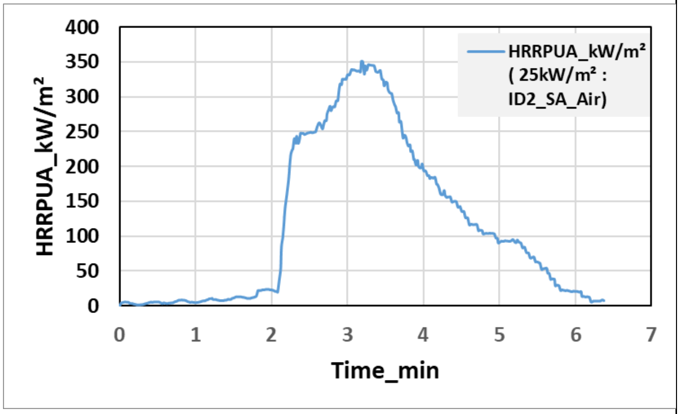

HRRPUA_kW/m²
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8
Time_min
HRRPUA_kW/m² (35kW/m² : ID6_V_Air)

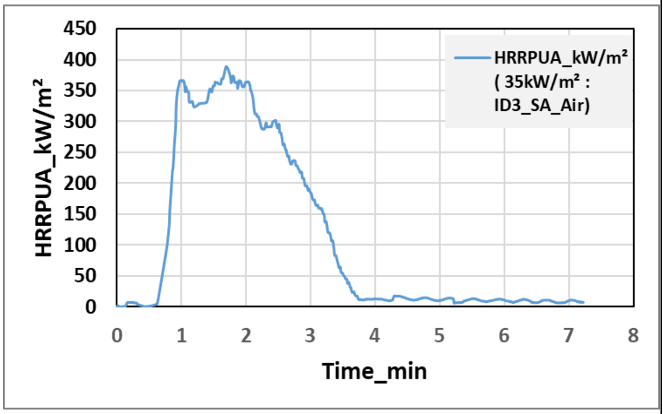

HRRPUA_kW/m²
350
300
250
200
150
100
50
0
0 1 2 3 4 5
Time_min
HRRPUA_kW/m² (50kW/m² : ID7_V_Air)

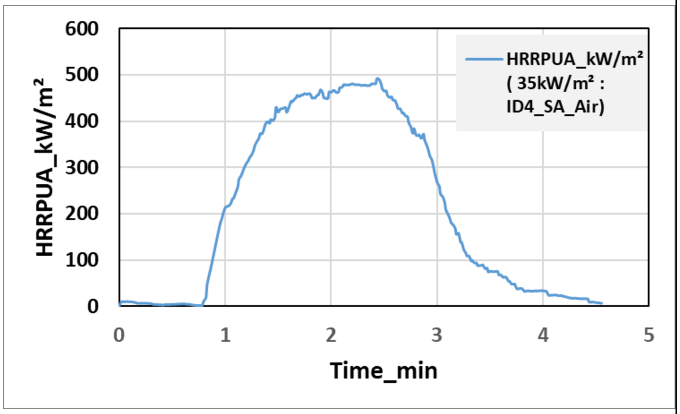

HRRPUA_kW/m²
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8
Time_min
HRRPUA_kW/m² (50kW/m² : ID8_V_Air)

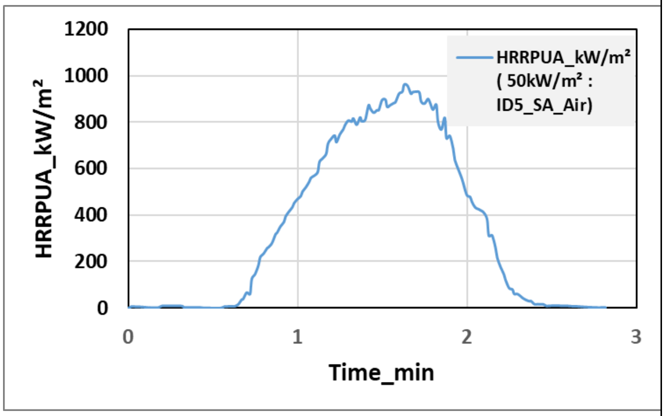

HRRPUA_kW/m²
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8
Time_min
HRRPUA_kW/m² (50kW/m² : ID9_V_Air)

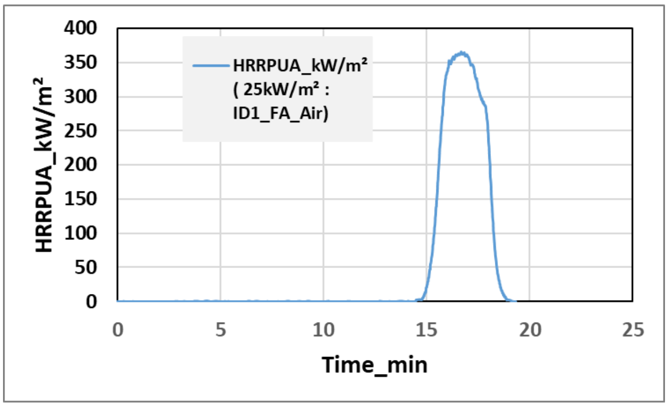

HRRPUA_kW/m²
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6
Time_min
HRRPUA_kW/m² (25kW/m² : ID1_SA_Air)

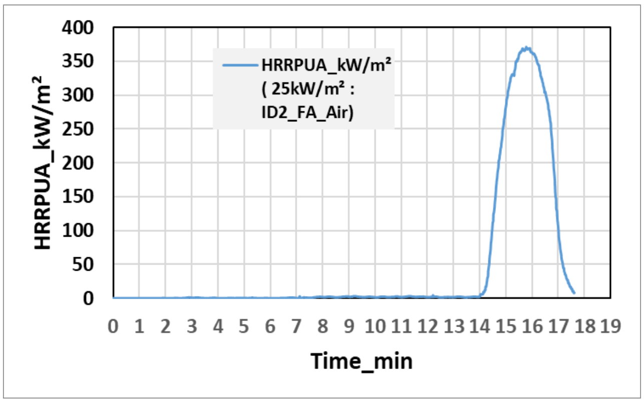

HRRPUA_kW/m²
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
Time_min
HRRPUA_kW/m² (25kW/m² : ID2_SA_Air)

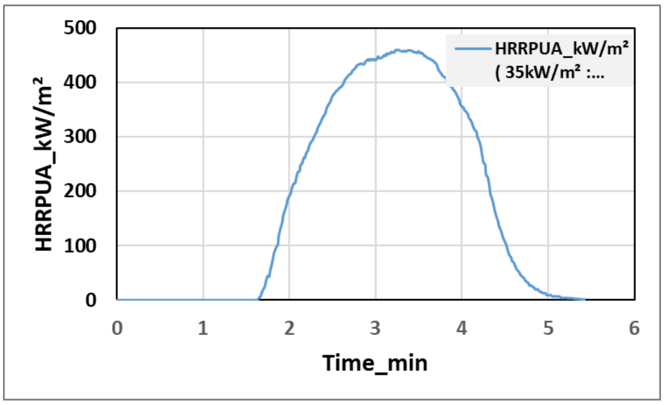

HRRPUA_kW/m²
450
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
Time_min
HRRPUA_kW/m² (35kW/m² : ID3_SA_Air)


HRRPUA_kW/m²
600
500
400
300
200
100
0
0
1
2
3
4
5
Time_min
HRRPUA_kW/m² (35kW/m² : ID4_SA_Air)

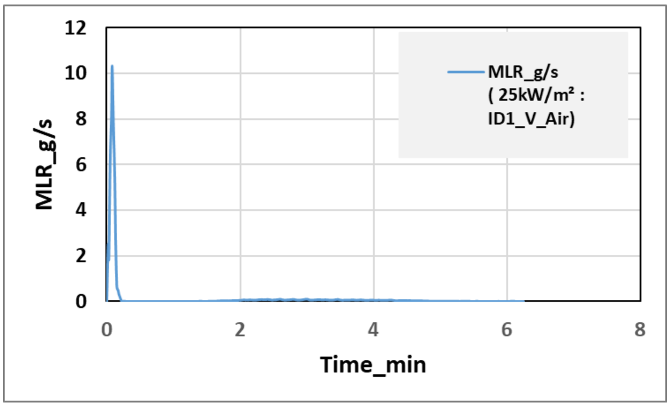

HRRPUA_kW/m²
1200
1000
800
600
400
200
0
0
1
2
3
Time_min
HRRPUA_kW/m² (50kW/m² : ID5_SA_Air)

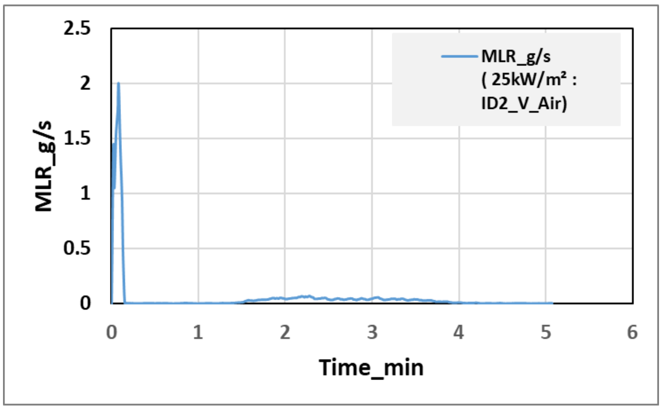

HRRPUA_kW/m²
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
Time_min
HRRPUA_kW/m² (25kW/m² : ID1_FA_Air)

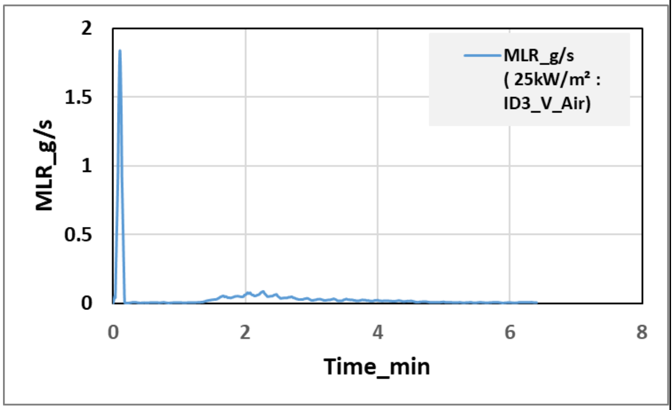

HRRPUA_kW/m²
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Time_min
HRRPUA_kW/m² (25kW/m² : ID2_FA_Air)

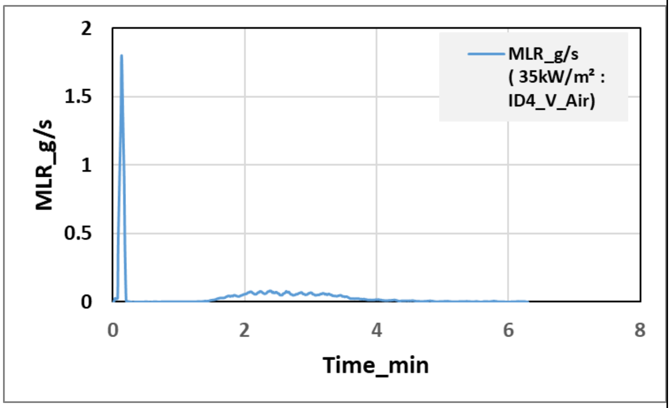

HRRPUA_kW/m²
500
400
300
200
100
0
0
1
2
3
4
5
6
Time_min
HRRPUA_kW/m² (35kW/m² :...

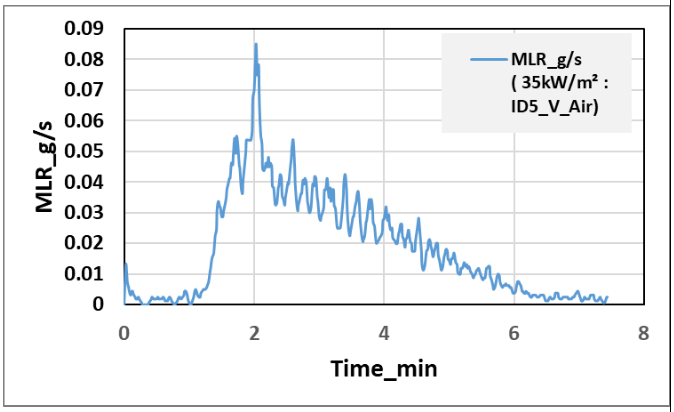
Charts of Mass loss rate (MLR) of all XLPE samples tested in cone calorimeter in air with spark

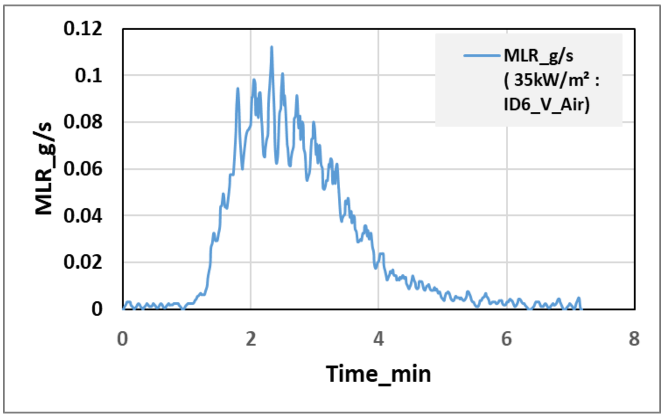


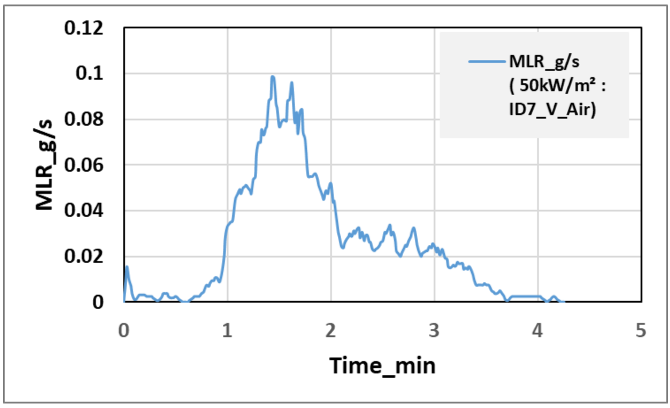


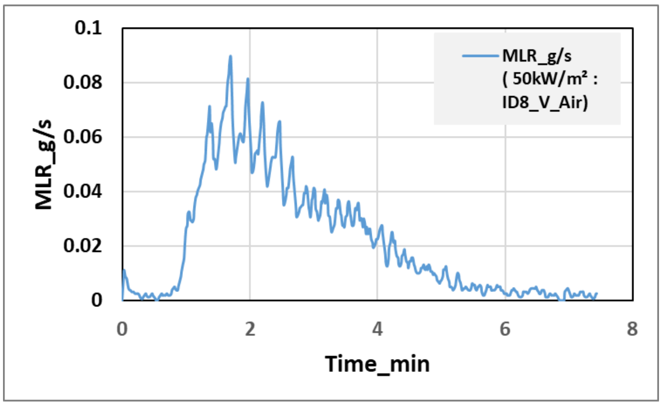


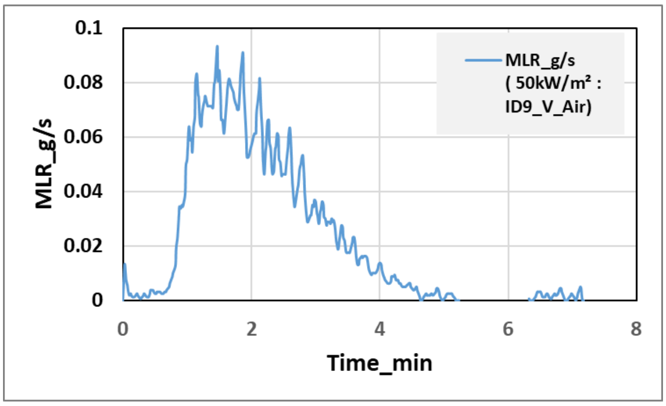


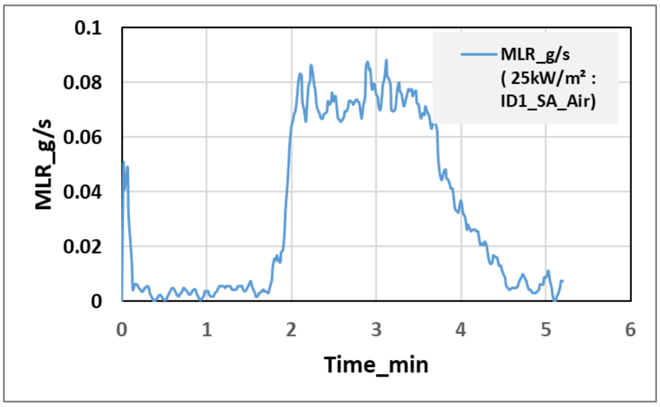


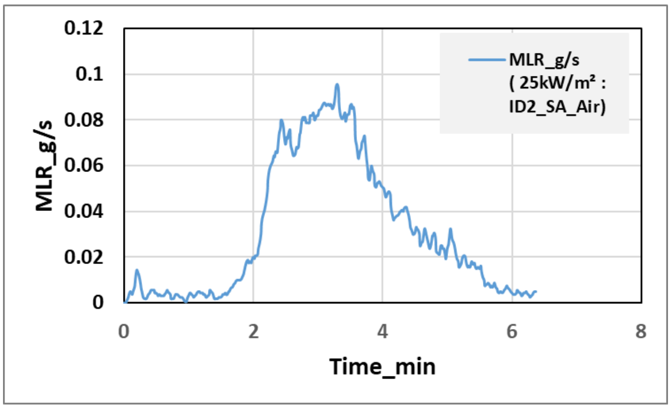


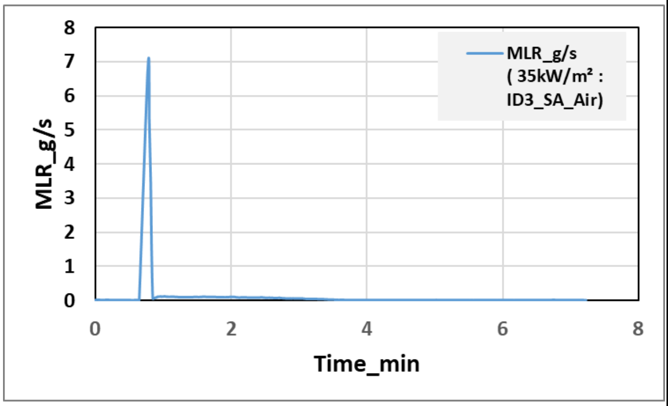


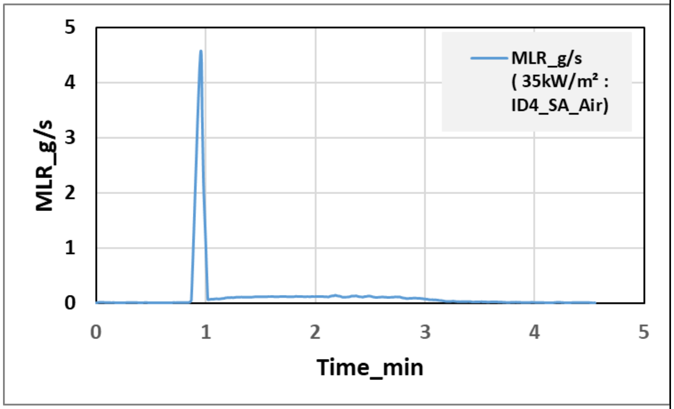


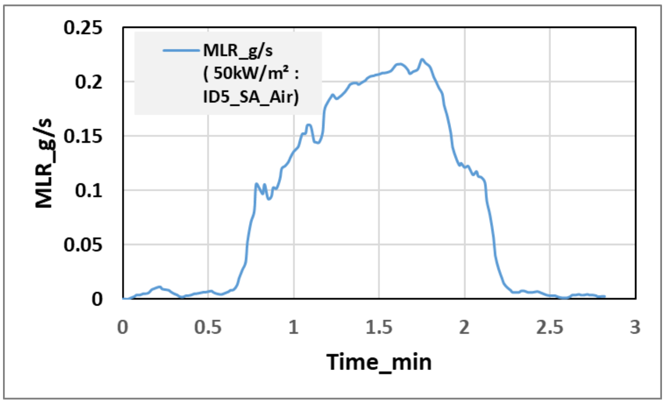

MLR_g/s
(50kW/m² : ID9_V_Air)
MLR_g/s
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
Time_min

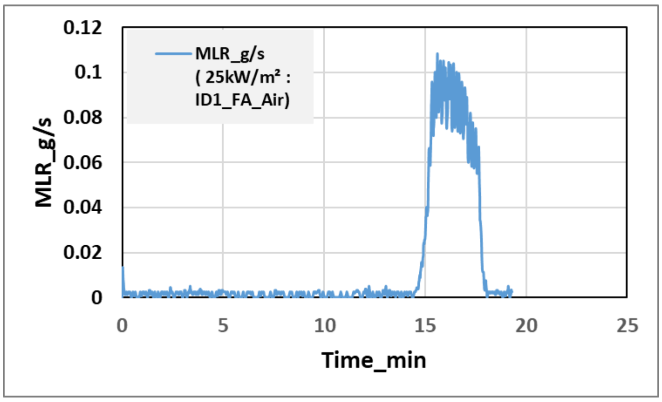

MLR_g/s
(25kW/m² : ID1_SA_Air)
MLR_g/s
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
6
Time_min

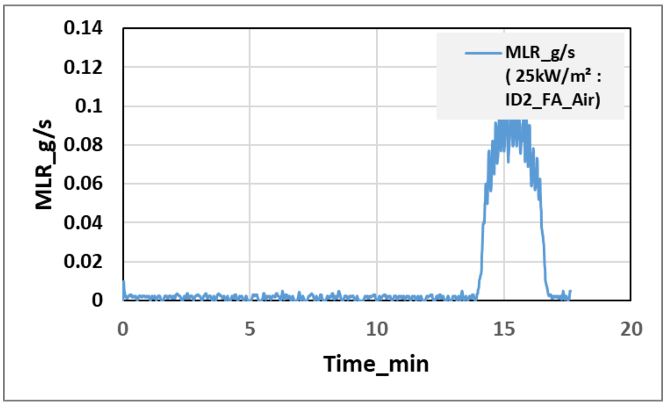

MLR_g/s
(25kW/m² : ID2_SA_Air)
MLR_g/s
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
Time_min

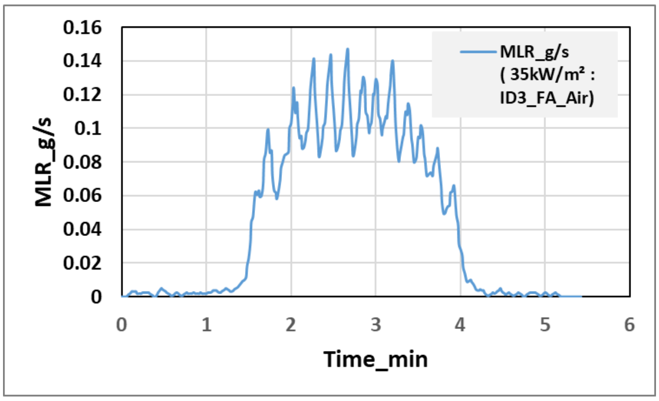

MLR_g/s
(35kW/m² : ID3_SA_Air)
MLR_g/s
8
7
6
5
4
3
2
1
0
0
2
4
6
8
Time_min


MLR_g/s
(35kW/m² : ID4_SA_Air)
MLR_g/s
5
4
3
2
1
0
0
1
2
3
4
5
Time_min


MLR_g/s
(50kW/m² : ID5_SA_Air)
MLR_g/s
0.25
0.2
0.15
0.1
0.05
0
0
0.5
1
1.5
2
2.5
3
Time_min


MLR_g/s
(25kW/m² : ID1_FA_Air)
MLR_g/s
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
Time_min


MLR_g/s
(25kW/m² : ID2_FA_Air)
MLR_g/s
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
Time_min


MLR_g/s (35kW/m² : ID3_FA_Air)
MLR_g/s
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
6
Time_min

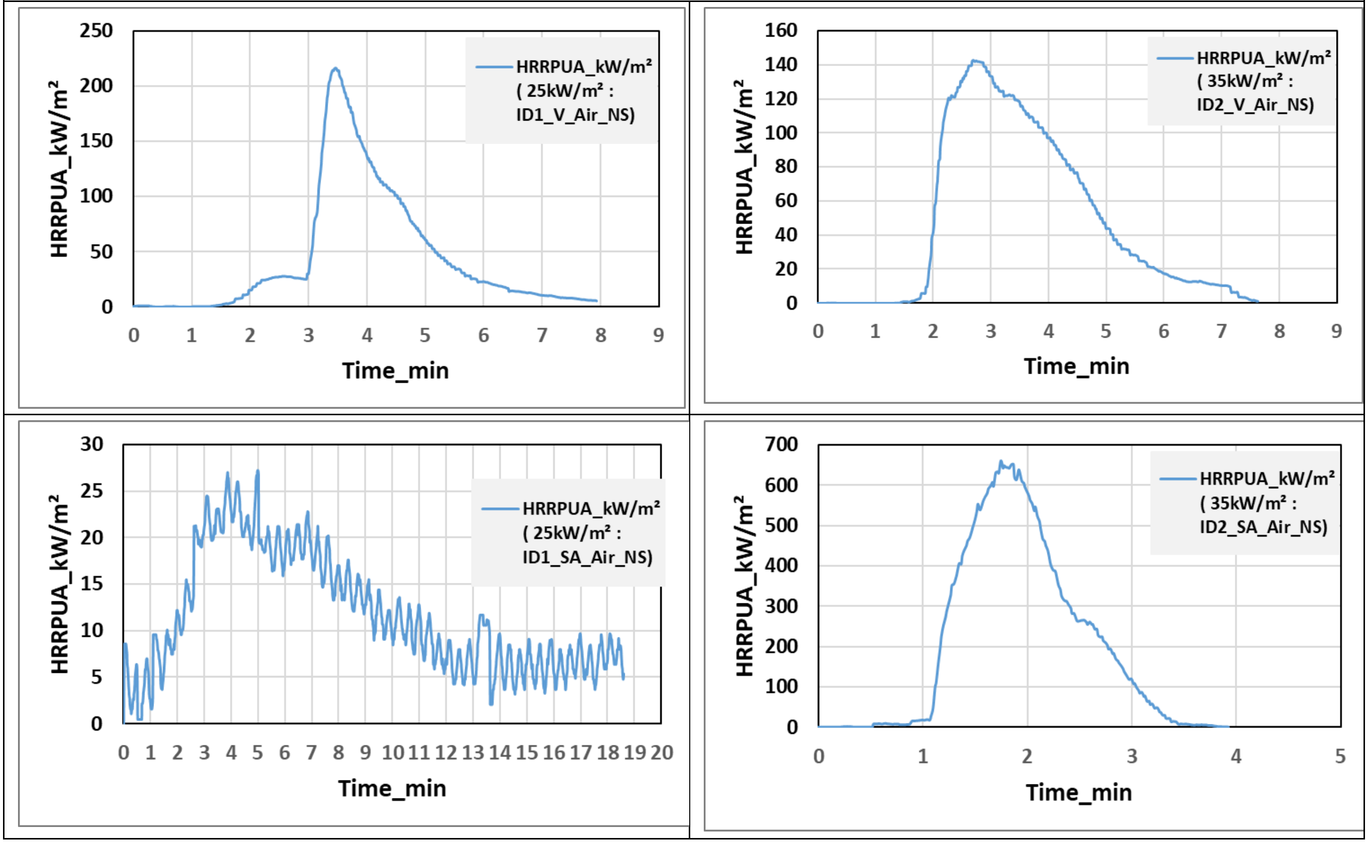
Appendix E: Heat Release Rate Per Unit Area (HRRPUA) and Mass loss rate (MLR) of all XLPE tested in cone calorimeter in air without spark

Table 4 is put here for quick reference for the test results.

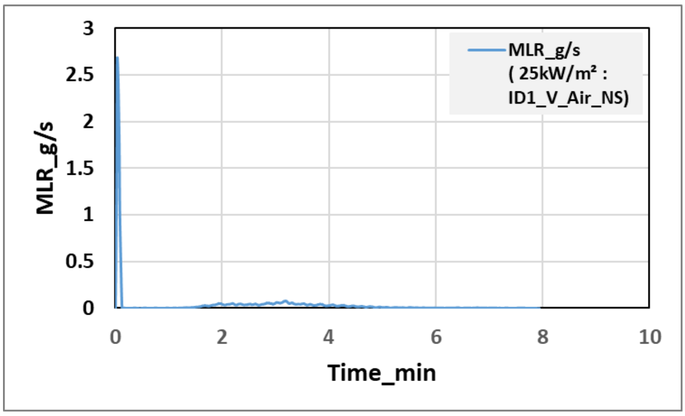
Table 4. Test plan B: Samples tested in cone calorimeter in air without spark.

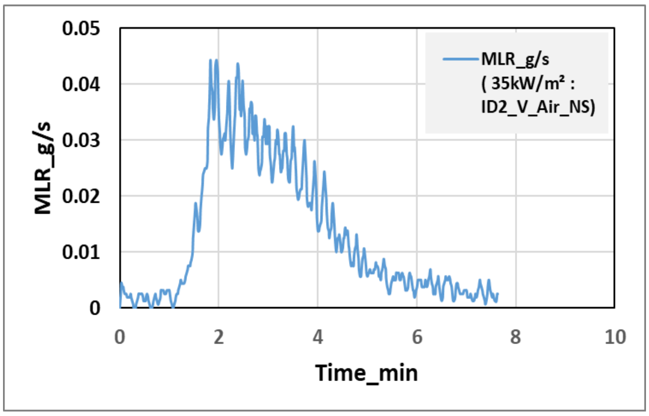
Test ID	Virgin/Slow-aged/Fast-aged	Heat Flux (KW/m²)	Chamber Gas	Spark	Remark (If any)
ID1_V_Air_NS	Virgin	**25**	Air	No	
ID2_V_Air_NS	Virgin	**35**	Air	No	
ID1_SA_Air_NS	Slow-aged	**25**	Air	No	
ID2_SA_Air_NS	Slow-aged	**35**	Air	No	
					V: Virgin; SA: Slow-aged; NS: No Spark

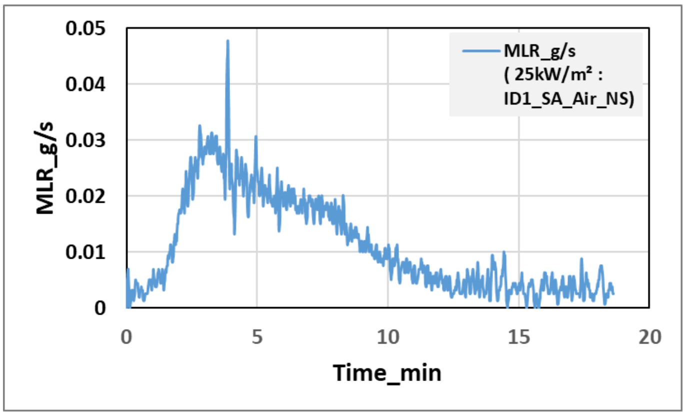
Charts of Heat Release Rate Per Unit Area (HRRPUA) of all samples XLPE tested in cone calorimeter in air without spark

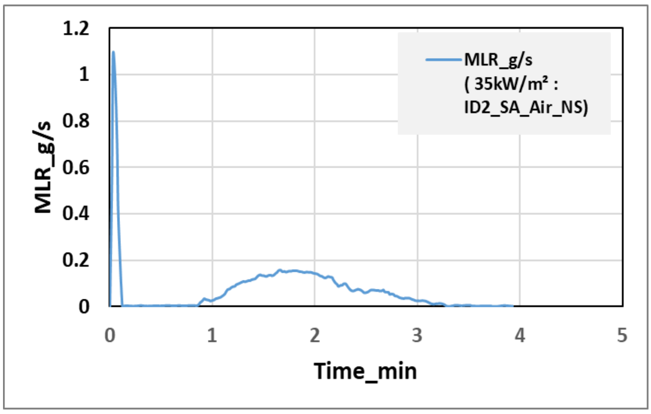


Charts of Mass loss rate (MLR) of all XLPE samples tested in cone calorimeter in air without spark









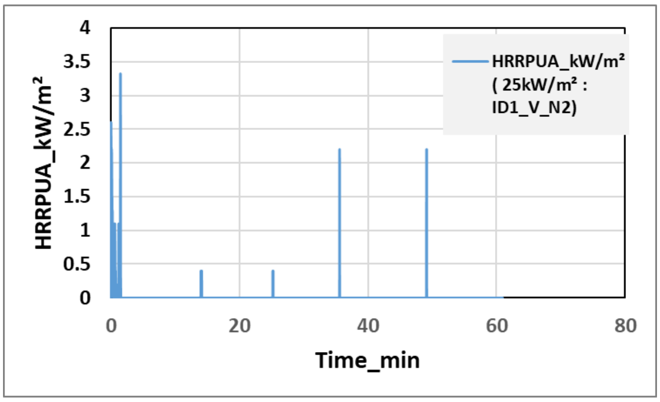
Appendix F: Heat Release Rate Per Unit Area (HRRPUA) and Mass loss rate (MLR) of all XLPE tested in cone calorimeter in Nitrogen

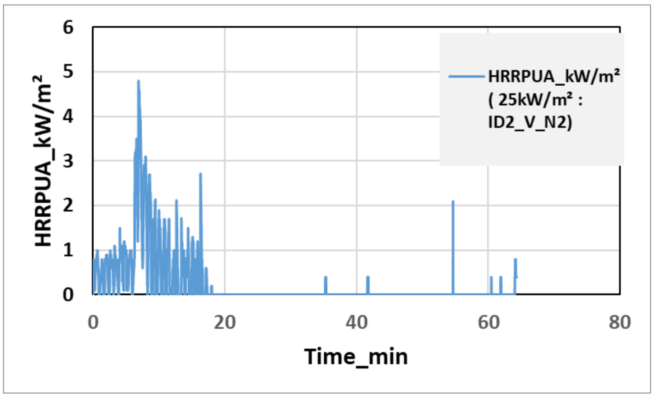
Table 5 is put here for quick reference for the test results.

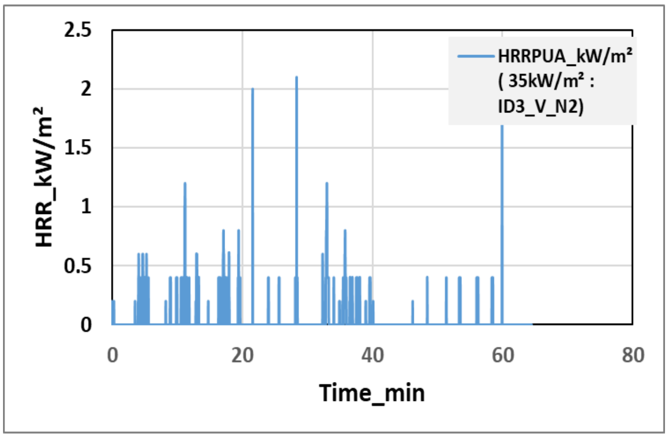
Table 5. Test plan C: Samples tested in cone calorimeter in nitrogen.

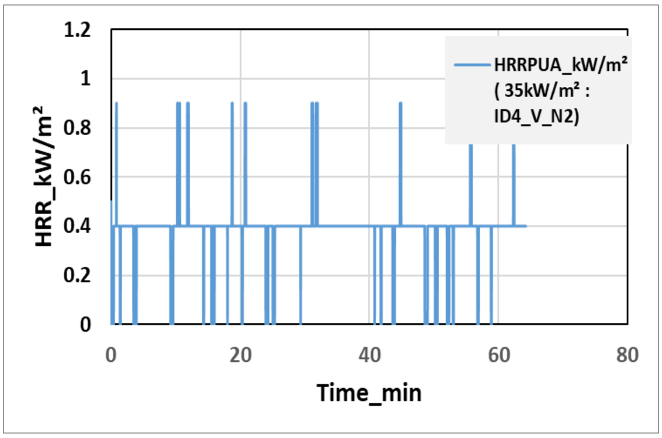
Test ID	Virgin/Slow-aged/Fast-aged	Heat Flux (KW/m²)	Chamber Gas	Spark	Remark (If any)
ID1_V_N_2	Virgin	**25**	Nitrogen	NA	
ID2_V_N_2	Virgin	**25**	Nitrogen	NA	repetition
ID3_V_N_2	Virgin	**35**	Nitrogen	NA	
ID4_V_N_2	Virgin	**35**	Nitrogen	NA	repetition
ID1_SA_N_2	Slow-aged	**25**	Nitrogen	NA	
ID2_SA_N_2	Slow-aged	**25**	Nitrogen	NA	repetition
ID1_FA_N_2	Fast-aged	**25**	Nitrogen	NA	
ID2_FA_N_2	Fast-aged	**35**	Nitrogen	NA	
V: Virgin; SA: Slow-aged; FA: Fast-aged					

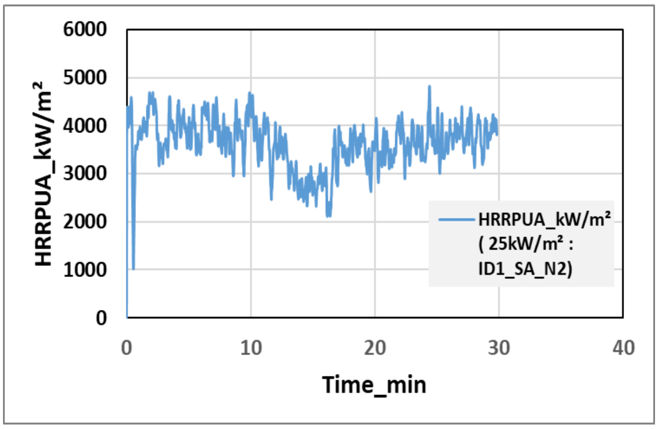
Charts of Heat Release Rate Per Unit Area (HRRPUA) of all XLPE samples tested in cone calorimeter in Nitrogen

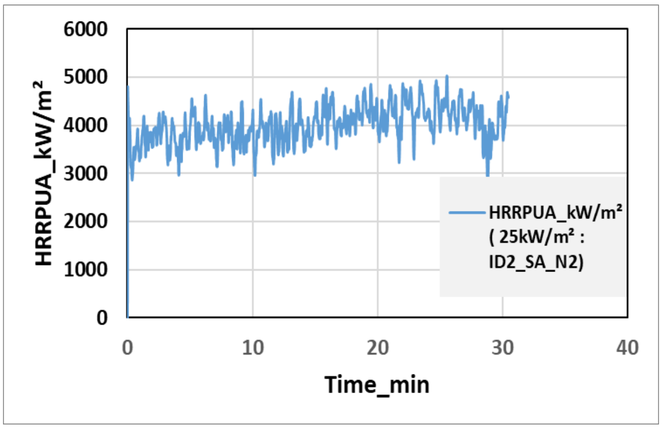


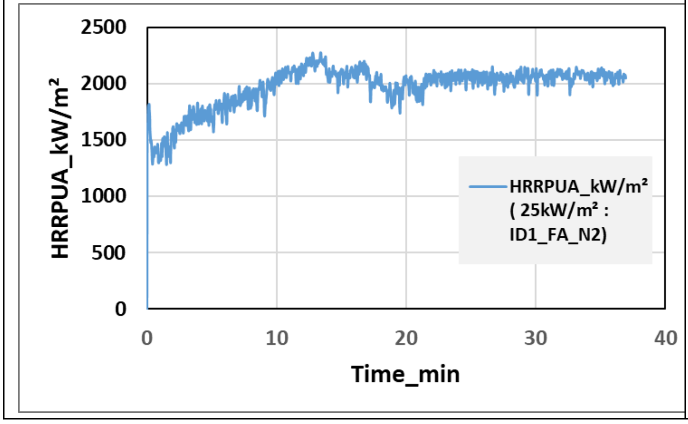


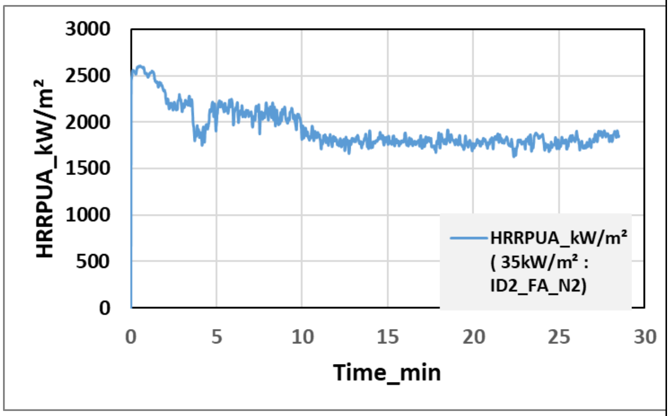




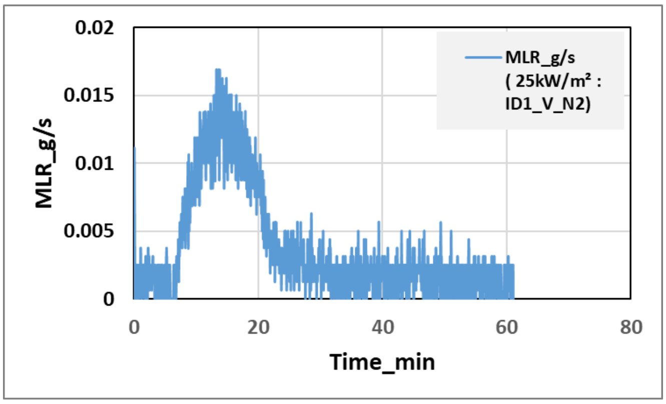


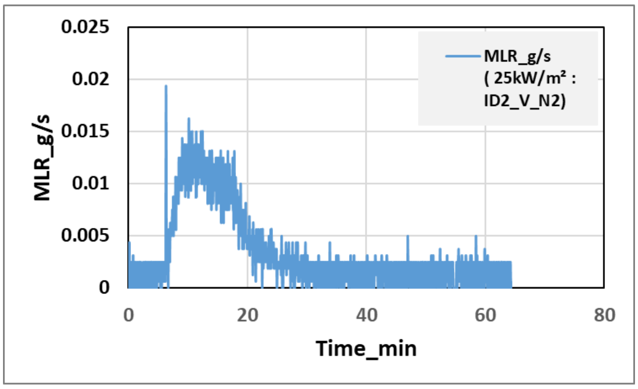


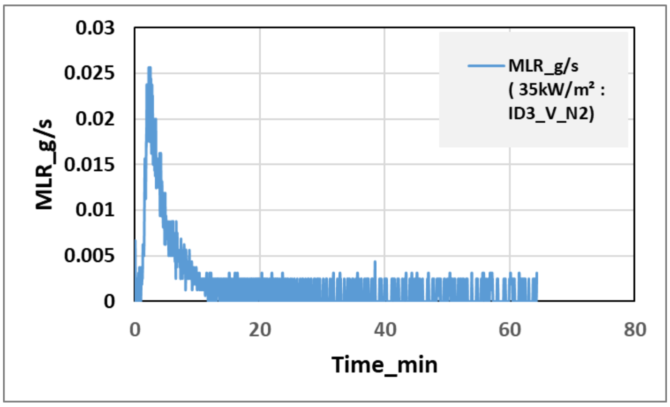


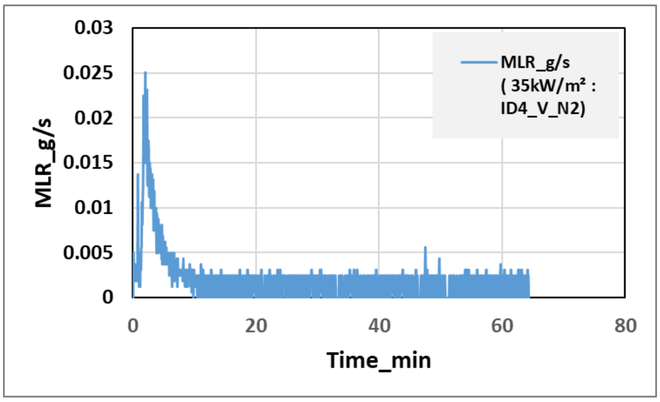


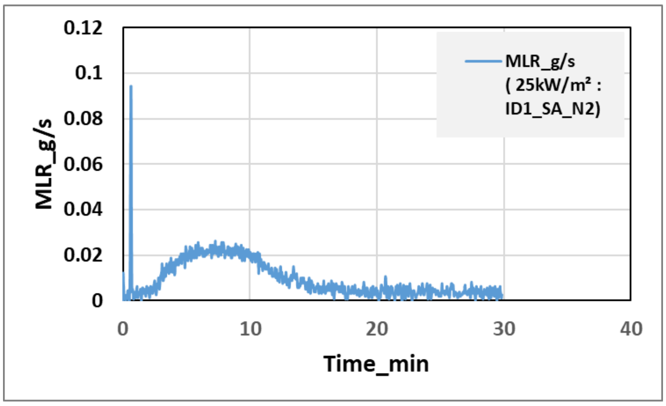
Charts of Mass loss rate (MLR) of all XLPE samples tested in cone calorimeter in Nitrogen

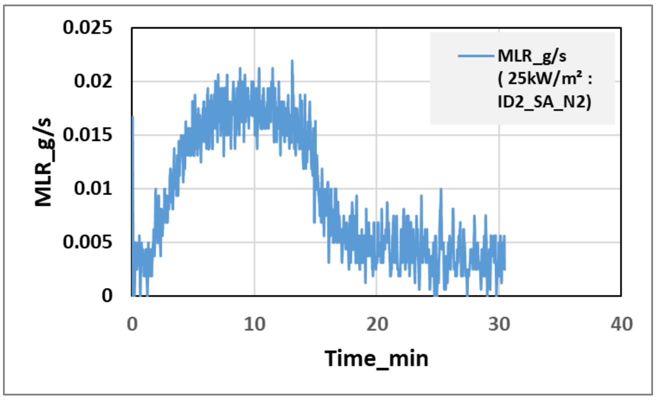


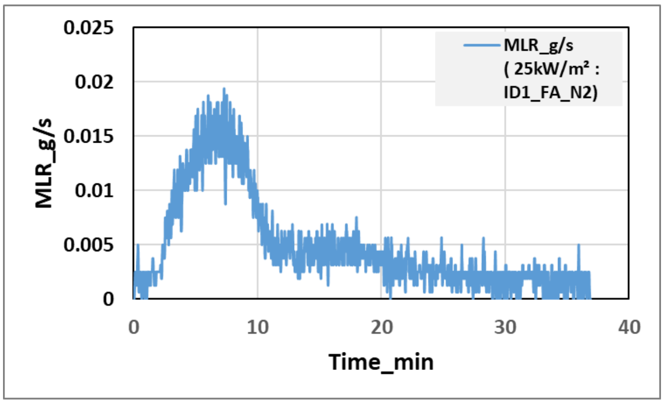


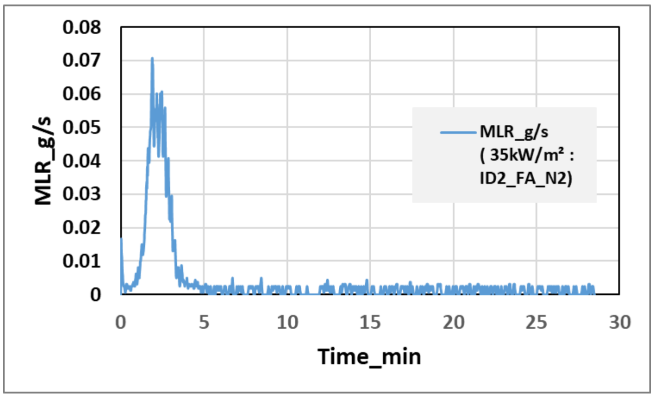





MLR_g/s
0.12
0.1
0.08
0.06
0.04
0.02
0
0
10
20
30
40
Time_min
MLR_g/s
(25kW/m² :
ID1_SA_N2)


MLR_g/s
0.025
0.02
0.015
0.01
0.005
0
0
10
20
30
40
Time_min
MLR_g/s
(25kW/m² :
ID2_SA_N2)


MLR_g/s
0.025
0.02
0.015
0.01
0.005
0
0
10
20
30
40
Time_min
MLR_g/s
(25kW/m² :
ID1_FA_N2)


MLR_g/s
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20
25
30
Time_min
MLR_g/s
(35kW/m² :
ID2_FA_N2)

Certificate Of Completion

Envelope Id: 6A1845C0-7DD7-47E8-93D4-D8687304CC96		Status: Completed
Subject: Complete with Docusign: VTT-R-00067-26 VTT_Research_Report		
Source Envelope:		
Document Pages: 46	Signatures: 1	Envelope Originator:
Certificate Pages: 2	Initials: 0	Christina Vähävaara
AutoNav: Enabled		Tekniikantie 21, Espoo
EnvelopeId Stamping: Enabled		., . P.O Box1000, FI-0204
Time Zone: (UTC+02:00) Helsinki, Kyiv, Riga, Sofia, Tallinn, Vilnius		Christina.Vahavaara@vtt.fi
		IP Address: 130.188.17.16

Record Tracking

Status: Original 30 January 2026 | 11:11	Holder: Christina Vähävaara Christina.Vahavaara@vtt.fi	Location: DocuSign

Signer Events	Signature	Timestamp
Napat Vajragupta Napat.Vajragupta@vtt.fi Research Team Leader Security Level: Email, Account Authentication (None), Authentication	Signed by: 88A44463BFC1495... Signature Adoption: Uploaded Signature Image Using IP Address: 2001:999:508:f989:d1fd:9aa3:99fa:6957	Sent: 30 January 2026 | 11:13 Viewed: 30 January 2026 | 11:33 Signed: 30 January 2026 | 11:33

Authentication Details
SMS Auth:
  Transaction: 2d263572-ec41-479f-8d3b-3069d9fdc7ed
  Result: passed
  Vendor ID: TeleSign
  Type: SMSAuth
  Performed: 30 January 2026 | 11:33
  Phone: +358 50 4626958

Electronic Record and Signature Disclosure:
  Not Offered via Docusign

In Person Signer Events	Signature	Timestamp

Editor Delivery Events	Status	Timestamp

Agent Delivery Events	Status	Timestamp

Intermediary Delivery Events	Status	Timestamp

Certified Delivery Events	Status	Timestamp

Carbon Copy Events	Status	Timestamp

Witness Events	Signature	Timestamp

Notary Events	Signature	Timestamp

Envelope Summary Events	Status	Timestamps
Envelope Sent	Hashed/Encrypted	30 January 2026 | 11:13
Certified Delivered	Security Checked	30 January 2026 | 11:33
Signing Complete	Security Checked	30 January 2026 | 11:33
Completed	Security Checked	30 January 2026 | 11:33

Payment Events	Status	Timestamps