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ENGENHARIA CIVIL

Contribution to Incorporation of Non-Recyclable Plastics in Bituminous Mixtures

Dissertação apresentada a provas públicas para a obtenção do grau de Mestre em Engenharia
Civil, orientada por:

Prof. Doutor Vítor Filipe Silva Antunes

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2025

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VERSÃO FINAL

Dissertação apresentada para a obtenção do grau de Mestre em Engenharia Civil no Curso de Mestrado em Engenharia Civil, Conferido pela Universidade Lusófona, Centro Universitário de Lisboa.

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Dissertação defendida em provas públicas na Universidade Lusófona, Centro Universitário de Lisboa no dia 13/03/2025, perante o júri, nomeado pelo Despacho de Nomeação n.º 204/2025, de 24 de fevereiro de 2025, com a seguinte composição:

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2025

Acknowledgements

I would like to express my deep gratitude to everyone who contributed to the conclusion of this thesis and throughout my academic career.

Firstly, I would like to thank my family and Cristiana for their unconditional support and endless patience, not only during the writing of this thesis but also throughout my academic career. Your support has been fundamental to the success of this journey.

To my supervisors, Vítor Antunes and Ana Cristina Freire, I thank you for your availability, for passing on your knowledge and for constantly challenging me. The opportunity to study such a fascinating subject would not have been possible without your guidance and encouragement.

To the National Laboratory for Civil Engineering and the Transportation Department, in the name of its Director, the Principal Researcher Doctor Maria de Lurdes Antunes, for the opportunity provided and for all the conditions and resources made available.

To IST and LVCT, in the Name of its Director, Professor Luís Picado Santos, for the tests performed.

To the laboratory technicians, José Reimão from LNEC and Rui Garcia from IST, I would like to thank you for your supervision and promptness during the laboratory tests. You were largely responsible for the success of the laboratory tests.

I would also like to thank Ambigroup for providing several plastic samples, Extruplás for generously making their facilities available for treating the plastic, Cepsa for supplying the bitumen needed for the tests, and Alves Ribeiro for providing the aggregates.

Resumo

Nos últimos 50 anos, a produção mundial de plástico registou um aumento exponencial, levando à procura de novas soluções que reutilizem estes resíduos. Este estudo explora a incorporação de resíduos plásticos não recicláveis em misturas betuminosas, pretendendo desenvolver uma solução sustentável com desempenho igual ou superior ao das misturas tradicionais para camadas de desgaste em pavimentos rodoviários. Selecionaram-se dez amostras de resíduos plásticos colhidos num centro de resíduos, onde apenas uma tinha valor comercial. Obtiveram-se 75 amostras após separação visual e ensaios de densidade. Avaliou-se o ponto de fusão dos plásticos, identificando os mais adequados para incorporar por via húmida. A via húmida revelou-se ineficaz devido à fusão parcial do plástico no betume. O estudo prosseguiu pela via seca, formulando-se uma mistura com 10% de plástico, validada através de ensaios Marshall. Posteriormente efetuou-se ensaios de sensibilidade à água, deformação permanente, fadiga, módulo de rigidez, macro e microtextura, recuperação de betume e uma avaliação ambiental e económica. Os resultados obtidos mostraram maior flexibilidade e resistência à água, elevada resistência à deformação permanente, menor rigidez e suscetibilidade a variações de frequência e temperatura. Estes resultados indicam que a adição de plástico melhora as propriedades das misturas betuminosas e reduz custos, oferecendo uma alternativa sustentável para os resíduos plásticos na construção de estradas.

Palavras chave: Misturas betuminosas, Plástico não reciclável, Reciclagem, Via húmida, Via seca

Abstract

Over the last 50 years, global plastic production has increased exponentially, leading to new solutions that reuse this waste. This study explores the incorporation of non-recyclable plastic waste into bituminous mixtures, with the aim of developing a sustainable solution with equal or better performance than traditional mixtures for road pavement surface courses. Ten samples of plastic waste were chosen in a waste centre, with only one having commercial value. Through visual sorting and density tests, 75 samples were derived. An initial evaluation of the plastics melting point was performed to assess their suitability for incorporation using the wet method. The wet method proved ineffective due to the partial melting of the plastic in bitumen. The study continued with the dry method, formulating a mixture with 10% plastic, validated through Marshall tests. Water sensitivity, permanent deformation, fatigue, stiffness, macro and microtexture tests were carried out, closing with bitumen recovery and an environmental and economic analysis. Results showed increased water resistance, high resistance to permanent deformation, reduced stiffness, lower susceptibility to frequency and temperature variations, and greater flexibility. These results indicate that the addition of plastic not only improves the properties of bituminous mixtures but also reduces costs, offering a sustainable alternative for non-recyclable plastics in road construction.

Keywords: Bituminous mixtures, Non-recyclable plastic, Recycling, Wet method, Dry method

Abbreviations, acronyms and symbols

BM – Bituminous Mixture;

CBM – Cold Bituminous Mixture;

E – Stiffness modulus;

E_1 – Real component of complex stiffness modulus;

E_2 – Imaginary component of complex stiffness modulus

E^* - Complex stiffness modulus

EVA – Ethylene-Vinyl Acetate

GHGs – Greenhouse gases;

GTR – Ground Tyre Rubber;

h – Height;

HBM – Hot Bituminous Mixture;

HDPE – High-Density Polyethylene;

HWBM – Half Warm Bituminous Mixture;

LDPE – Low-Density Polyethylene;

m_1 – dry specimen mass;

m_2 – the mass of the saturated specimen;

m_3 – the mass of the saturated specimen with dry surfaces;

m_4 – the mass of the empty pyknometer including the head piece;

m_5 – the mass of the pyknometer filled with distilled water including the head piece;

m_6 – mass of the pyknometer with the dry sample including the head piece;

m_7 – the mass of the pyknometer filled with distilled water and the sample including the head piece;

PE - Polyethylene;

PET – Polyethylene Terephthalate;

OBC – Optimum Bitumen Content;

PP – Polypropylene;

PRD_{AIR} – Proportional Rut Depth;

PS - Polystyrene;

PTV – Pendulum test value

PVC – Polyvinyl Chloride;

RAP – Reclaimed Asphalt Pavement;

RAR – Reacted and Activated Rubber;
RCA – Recycled Concrete Aggregates;
 RD_{AIR} - Mean rut depth at 10.000
SBS – Styrene-Butadiene-Styrene
TLPP – Thin Liquid Polyol PET;
 v – Volume;
 v_2 – Volume after vacuum;
VMA - Voids in the mineral aggregate;
VPP – Viscous Polyol PET;
WBM – Warm Bituminous Mixture;
 WTS_{AIR} – Wheel tracking slope;
4PBT – Four-point bending test;
 Φ - Diameter;
 ϕ – Phase angle;
 Δv – Variation of volume;
 ρ_w – Density of the water;
 ρ_b – Density of the bitumen;

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1 Introduction

1.1 Background and motivation

The development of road infrastructure is critical for the socioeconomic growth of societies as it facilitates the transport of goods and people. However, the major challenge of road construction lies in identifying durable, economically feasible, socially inclusive and ecologically sustainable materials. This challenge is particularly urgent given the increasing demands on infrastructure and the need to address environmental sustainability, without significant cost increases.

Plastics play an important role in various sectors of our society due to their versatility, resistance, and low production cost. Nevertheless, the excessive production of plastics has resulted in a significant environmental concern, as it is a non-biodegradable material with only around 33% of the plastic packaging generated in Europe being recycled in 2020 (Eurostat, 2022)(Willis et al., 2020) Plastic waste has become abundant in our environments.

The integration of recycled materials in bituminous mixtures (BM) for road construction is not a new concept. The incorporation of Reclaimed Asphalt Pavement (RAP) (Antunes et al., 2023; Pradyumna & Jain, 2016), tyre rubber (Brasileiro et al., 2019; Willis et al., 2020), fly ash (Melotti et al., 2013; Usman et al., 2021), steel slag (Skaf et al., 2016, 2021) and recycled construction and demolition materials (Karakuş, 2011; Nwakaire et al., 2020), among others, have already been studied. The use of plastic in bituminous mixtures is a promising solution to enhance the short- and long-term performance and resilience of road pavements while addressing the plastic waste issue.

Several types of plastic, including polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP) have been incorporated into bituminous mixtures. The selection of plastic types is crucial to obtain an effective modification of the bitumen and/or bituminous mixture's properties. The melting point, shapes and sizes of the plastic materials must also be considered (Willis et al., 2020).

The incorporation of plastic into bituminous mixtures exhibited substantial improvements in the properties of the mixtures. These enhancements include increased Marshall stability, polishing resistance, fatigue resistance, permanent deformation resistance, adhesion, water resistance, stiffness and increasing road maintenance periods, due to the

increase in durability of the solutions (Brasileiro et al., 2019; Gürü et al., 2014; A. B. Khan & Jain, 2020; Ranieri et al., 2017).

Different methods have been used to incorporate plastic into bituminous mixtures, including wet, dry, and semi-wet methods. The wet method involves adding plastic directly to the heated bitumen, allowing the plastic to melt and the modification of the bitumen (Sasidharan et al., 2019; Willis et al., 2020). The dry method involves mixing the plastic with the heated mineral aggregate before adding the bitumen (Gawande et al., 2012; Sasidharan et al., 2019). The semi-wet method uses a long digestion process before joining the material with the bitumen (Picado-Santos et al., 2020). Each technique has its advantages and disadvantages, and the selection between them depends on the characteristics of the plastic, the composition of the desired mixture, the specific objectives of the road paving application and the equipment that is available to perform each technique. It is imperative to comprehend the differences between each method to determine the most suitable technique for the production process and desired properties of plastic-modified bitumen and/or bituminous mixtures.

In summary, incorporating plastic waste into bituminous mixtures not only presents a practical solution for enhancing road strength and performance but also introduces an innovative approach to addressing the environmental impact of plastic waste. This dual benefit underscores the importance of continuous research and development in this field, with the potential to make significant progress in both infrastructure resilience and environmental sustainability.

1.2 Objectives and methodology

The main focus of this dissertation is to identify an effective solution for the management of plastic waste that is not recyclable or reusable. The proposed solution involves incorporating the non-recyclable plastic waste into bituminous mixtures for surface courses. The primary objectives of this study are to enhance the properties of bituminous mixtures by integrating plastic waste and to decrease the use of raw materials, specifically the quantity of bitumen necessary for their production. Additionally, the aim is to improve the economic viability of the BM by reducing raw material consumption through the addition of plastic waste, thereby offsetting the investment in the incorporation process. The investments include the collection, transportation, and treatment of the waste.

To achieve this objective, a set of laboratory tests were conducted at the LNEC Transport Department and at the Instituto Superior Técnico to identify and select the most promising waste, suitable methods and formulations:

Ten different samples of plastic waste were collected from a waste treatment centre. These samples encompassed both heterogeneous and homogeneous plastic wastes. The samples were analysed in detail, and the constituents present in each heterogeneous sample were separated by type of plastic, density and colour. The melting temperatures of each plastic sample and sub-sample were identified to determine the samples that were suitable for incorporation into bituminous mixtures.

After analysing the ten samples, some of them were chosen for incorporation into the bituminous mixtures using the wet and dry method. A comparative analysis of both methods revealed that the dry method was more suitable, incorporating 10% of plastic waste in relation to the total weight of the bituminous mixture. A dense graded bituminous mixture with a maximum aggregate size of 14 mm and a net bitumen with nominal penetration of 35/50 (AC 14 surf 35/50), was used as reference.

To optimize the bituminous mixture behaviour, Marshall and density tests were conducted to determine the optimum bitumen content. Once the optimum bitumen content was established, a set of laboratory tests to assess the functional and mechanical behaviour was performed. Regarding the functional performance, it was performed the macro- and micro-texture evaluation. To evaluate the mechanical behaviour, it was evaluated water sensitivity, fatigue resistance, stiffness modulus, and permanent deformation resistance. These tests aimed to assess the performance of bituminous mixtures that incorporate plastic waste under different conditions of use and to determine whether the incorporation process was a viable solution.

1.3 Work structure

This thesis is divided into five chapters, each contributing to a comprehensive understanding of the subject.

Chapter 1 introduces the topic, emphasizing the importance of pavements, the issue of plastics and the objective of incorporating plastics into bituminous mixtures. The methodology utilized is also outlined.

Chapter 2 introduces key concepts relevant to the subject, starting with an overview of plastic, its societal significance, recycling practices, and the environmental impact of its

overuse. It then transitions to discussing pavement types, defining bituminous mixtures, and describing the various layers that make up a pavement structure. The chapter concludes by addressing the core topic of the dissertation, exploring existing methods for producing bituminous mixtures, the types of plastics currently integrated, and the potential enhancements that could be realized.

Chapter 3 presents the plastic samples tested and the various laboratory tests performed, including the methodology used and the variations according to the standard.

Chapter 4 presents the discussion and analysis of the results obtained from the different laboratory tests conducted.

Chapter 5 presents an environmental and economic analysis of the bituminous mixture studied and compares it with a reference mixture.

Chapter 6 discusses the conclusions of the results obtained in the laboratory tests. It also recommends future works that can provide a better understanding of the subject.

Annexes including additional information on the various tests conducted, are also included.

2 Literature review

Plastic is a highly versatile material, and this section will present the different types of plastic, their applications, recyclability, environmental problems and the health risks linked to each type.

Furthermore, the sizes of plastic found in the environment will be analysed, which can be classified as macro, micro and nano-plastic, with different interpretations of their dimensions.

Focus will be given to the environmental impact of plastic production and disposal, highlighting the importance of recycling as a key strategy to reduce this impact, despite the challenges it presents. Additionally, the use of plastics in construction and the environmental issues stemming from their overuse will be explored in depth.

The different types and functions of pavements, as well as the materials that compose them, will also be explored. Specifically, bitumen and its layered composition in flexible pavement, as well as the production techniques involved, will be focused on.

Moreover, recycled materials, such as tyre rubber, will be examined closely, and the advantages and disadvantages of incorporating them into bituminous mixtures will be considered.

Lastly, the types of plastic incorporated and the characteristics that bituminous mixtures acquire with their incorporation will be mentioned. A distinction will also be made between the wet, dry and semi-wet methods and their advantages and disadvantages, to help select the most suitable method for a given application.

2.1 General considerations

Plastics play an essential role in the modern world and are challenging to replace. Their strength, flexibility, and low production costs make them ideal for manufacturing a wide variety of products. Plastics are commonly used in food packaging, cosmetics, healthcare, transportation, clothing, and many other applications.

The plastics industry is massive. In 2021, producers of raw materials, plastics manufacturers, recyclers, and machinery fabricators formed a supply chain that employed more than 1.5 million people across Europe. These companies generated a turnover of around 40 billion in European public finances (Plastics Europe, 2022).

Every year more plastic is produced. Figure 2.1 shows the increasing production of plastic since the beginning of the 21st century. Currently, 380 million tonnes of plastic are produced, and half of this amount is used in single-use packages, sometimes with a time of use of minutes, or even seconds (PlasticOceans, 2022).

As a non-biodegradable material with a recycling rate of 9%, it is found in enormous quantities all over the planet, even in the most remote areas. Leading to one of the main environmental crises of the 21st century (PlasticOceans, 2022).

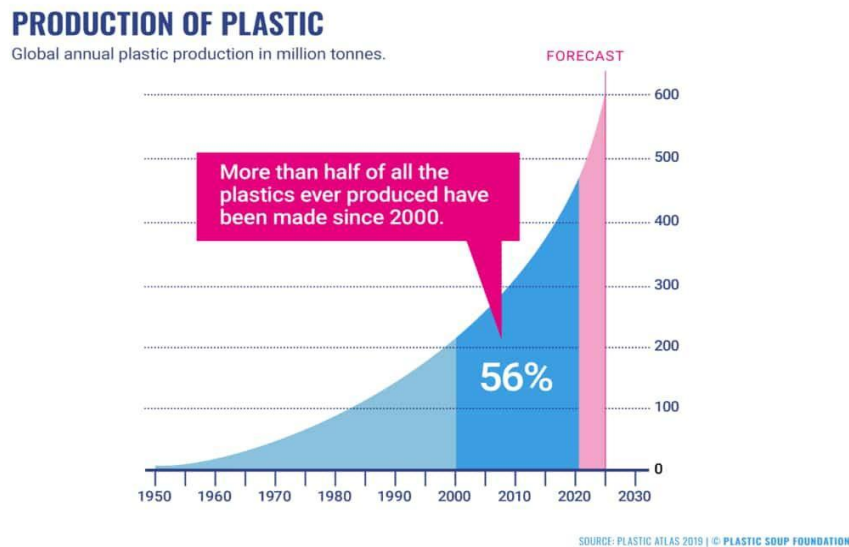


Figure 2.1 - Global annual plastic production (Plastic Soup Foundation, 2021)

2.2 The problem of plastics

The name plastic comes from the Greek word ‘Plastikos’ which means flexible. The plastics consist of polymer molecules, which are a chain of monomers.

The length of these chains, along with the production process, such as temperature and pressure at which the plastic is processed, will determine the material’s properties. This allows for the creation of plastics that are either flexible or nearly as strong as metal.

Plastics can be classified as either thermoplastic or thermoset. Thermoplastics soften when heated, allowing them to be melted and reshaped. Examples of this group include bottles, clothing and polyester film. These plastics are recyclable, though their properties degrade with each recycling cycle, limiting the number of times they can be reused. In contrast, thermoset plastics, as shown in Figure 2.2, cannot be melted after production, as they remain solid even when heated. These are commonly used in products like electrical sockets and boat hulls (Plastic Soup Foundation, 2023).



Figure 2.2 - Thermoset plastic (*Airtasker AU*, 2023)

Plastic can be of synthetic or bio-based origin. The first is derived from crude oil, coal and natural gas. While the bio-based ones come from biomass, for example, maize, sugarcane and cellulose. Today, the majority of plastic production is synthetic, beginning with the extraction and processing of crude oil (Baheti, 2023).

Following extraction, the refining process begins, producing monomers. These monomers undergo polymerization reactions, resulting in the formation of polymeric resins. The resins are then collected and further processed to create pellets, as illustrated in Figure 2.3. These pellets are eventually heated and moulded into the final product (Baheti, 2023; Craig Freudenrich, 2023).



Figure 2.3 - Plastic pellets (*tinsleyequipmentcompany*, 2022)

2.2.1 Types and sizes of plastics in the environment

Plastics can come in a wide range of shapes, colours and sizes, and their varying compositions result in different types of plastics. As presented in Table 2.1, plastics can be categorised into seven main groups, according to their intrinsic properties and different uses.

Knowing the different types of plastic is essential for effective recycling and for assessing the health risks associated with each type (Umapathy, 2019).

Table 2.1 - Types of plastic

Types of plastic	Recycling code	Chemical formula	Melting point (°C)	Density (g/cm ³)	Advantages	Disadvantages	Uses	References
PET - Polyethylene Terephthalate	#1	(C ₁₀ H ₈ O ₄) _n	240 - 270	1.3 - 1.4	- Light and flexible; - Safe for contact with drinks and food; - 100% recyclable	- Lower heat resistance; - Oxidation of the plastic can lead to a degradation of taste in foods and drinks; - Poor resistance to UV and heat;	- Food and beverage containers; - Disposable cups and bottles; - Clothing.	(Omnexus, 2023; Xometry, 2023)

Types of plastic	Recycling code	Chemical formula	Melting point (°C)	Density (g/cm ³)	Advantages	Disadvantages	Uses	References
HDPE - High-Density Polyethylene	#2	(C ₂ H ₄) _n	120 - 140	0.941 – 0.965	- Resistant to most solvents; - Safe to reuse; - Easily recyclable;	- May release chemicals that disturb the human hormonal system; - Not very resistant to UV and heat; Susceptible to cracking and fissuring;	- Butter and yoghurt packaging; - Detergent and shampoo packaging; - Waste containers.	(Almack, 2023; Omnexus, 2023)
PVC - Polyvinyl Chloride	#3	(C ₂ H ₃ Cl) _n	170 - 210	1.300 – 1.700	- Good electrical insulator; - Resistant to corrosion and weathering; - Long life service with little need for maintenance;	- Material properties may change over time; - Can release dangerous toxins during its life cycle; - Complicated recycling process;	- Blood storage bags; - Window frames; - Car seats.	(A&C Plastics, 2023; Omnexus, 2023.)
LDPE - Low-Density Polyethylene	#4	(C ₂ H ₄) _n ;	105 - 115	0.910 – 0.925	- Safe to reuse; - Flexible; - Safe for contact with beverages and food;	- Complicated recycling process; Highly flammable; - Not very resistant to UV and heat;	- Food and frozen packaging; - Squeezable bottles or containers; - Plastic bags.	(Almack, 2023; Omnexus, 2023.)

Types of plastic	Recycling code	Chemical formula	Melting point (°C)	Density (g/cm ³)	Advantages	Disadvantages	Uses	References
PP - Polypropylene	#5	(C ₃ H ₆) _n	160	0.900 – 0.910	- Safe for contact with beverages and food; - Good resistance to cracking; - Excellent resistance to acids, alcohols and bases;	- Complicated recycling process; - Highly flammable; - Vulnerable to microbial attacks;	- Take away packaging; - Straws; - Packaging that can be heated.	(Hardin, 2021; Omnexus, 2023.)
PS - Polystyrene	#6	(C ₈ H ₈) _n	240	1.050	- Low-cost plastic; - Easy production; - Extremely light;	- Not recyclable; - May release toxins when in contact with food; - Easy to spread in the environment;	- Filler in product packaging; - Bicycle helmets; - Plastic cutlery.	(Almack, 2023; Hardin, 2021)
Others - Acrylic, Nylon, ...	#7	Depends on plastic type	Depends on plastic type	Depends on plastic type	-	- Normally not recyclable;	- CD's; - Contact lenses; - Baby bottles.	(Hardin, 2021)

The plastic found in the environment presents various sizes and can be classified as macro, micro and nano-plastic. There is no consensus on their dimensions.

While some authors say that macro-plastics are larger than 20 millimetres, micro-plastics range between 1 micrometre and 5 millimetres and nano-plastics are smaller than one micrometre (Costa et al., 2016). Others say that macro-plastics are larger than 5 millimetres (Bakas et al., 2021).

Considering the nomenclature and the definition of scales presented in the International System of Units, macro-plastics should be all plastics seen through the naked eye, while the other two should contain the dimensions according to the international system, where micro-plastics correspond to the micrometre scale (10^{-6}) and nano-plastics to the nanometre scale (10^{-9}).

Macro-plastics are very common in people's lives as they are used by a large proportion of the world's population daily, e.g. plastic bags, water bottles, single-use packages. These macro-plastics should be collected and recycled, however with low recycling rates (Costa et al., 2016).

Micro-plastics can vary between primary and secondary micro-plastics. Primary micro-plastics are added to products to improve a certain property (EEA, 2021). They can be found in cosmetics, for exfoliating and glittering, or synthetic sports fields with the use of granulated tyre rubber (Lusa., 2020). Secondary micro-plastics, on the other hand, are formed through the degradation of larger plastics. The degradation of plastics can be of chemical, physical and biological origin (EEA, 2021; Plastics Europe, 2023).

Lastly, nano-plastics, are formed through the degradation of microplastics (Costa et al., 2016). Figure 2.4 shows a comparison of the types of plastic mentioned above.

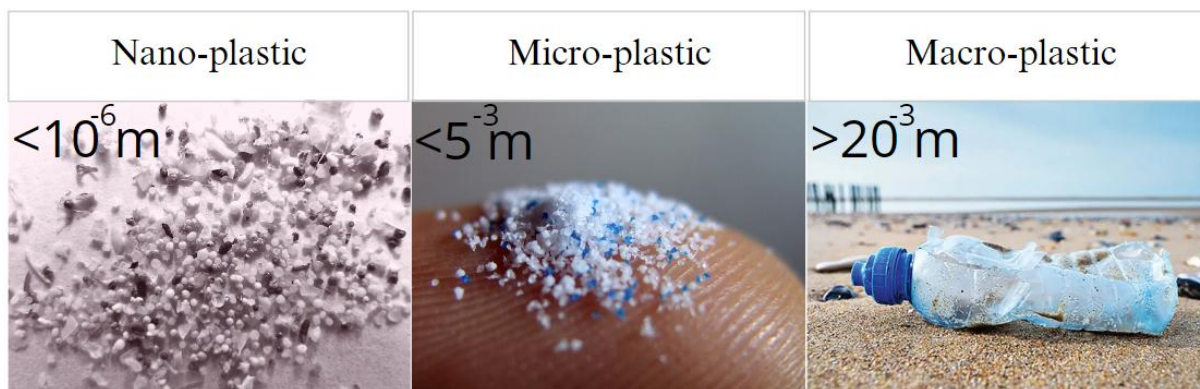


Figure 2.4 - Comparison of the size of nano-plastics, micro-plastics and macro-plastics according to (Costa et al., 2016)

2.2.2 Recycling

Recycling is essential to give a new life to plastics which are consumed worldwide, preventing them from being incinerated, landfilled or discarded into the environment. In addition, to reduce and reuse policies, recycling is the best solution to the plastic crisis. However, it still faces limitations, as it is not always environmentally, economically, or technically viable (Plastics For Change, 2022).

Recycling can be challenging when items are made from multiple types of plastics or materials with different layers that are difficult to separate. Contamination from food or other substances can also prevent plastics from being effectively recycled, as it impairs the ability to reuse the resins. Additionally, most plastics can only be recycled a few times because the polymers degrade during the recycling process. The food industry poses another challenge, as it generates a significant amount of single-use packaging, much of which is used for only a few minutes or even seconds. Economically, recycling centres need to process large volumes of plastic daily to remain profitable, adding another layer of complexity to the recycling process (Plastics For Change, 2022).

Before the recycling process, the plastic is washed and decontaminated, followed by a sorting process to separate the plastics according to their type of polymer, colour, density and melting point. Recycling methods include mechanical, chemical, dissolution or organic type. Among these, mechanical and chemical recycling are the primary methods, with mechanical recycling being the most common (Plastics Europe, 2021; Plastics For Change, 2022; Willis et al., 2020).

In mechanical recycling, the plastics are shredded, then melted into small pellets and moulded to obtain the desired product without significantly changing its chemical structure. Generally, all types of thermoplastics can be mechanically recycled without compromising the quality of the recycled material (Plastics Europe, 2021; Plastics For Change, 2022).

Chemical recycling aims to change the chemical structure of polymer waste, so it can be transformed into raw material for plastic production. Different chemical recycling technologies can be used, such as pyrolysis, gasification and depolymerisation. It tends to be a more expensive process than mechanical recycling. Its main advantage is that it can recycle plastics that are not normally recycled through the mechanical process, such as PVC (Nielsen & Bauer, 2019; Plastics Europe, 2023).

Other recycling methods are not as widely used as the two methods mentioned previously which are dissolution recycling and organic recycling. In dissolution recycling, a

purification process is used where the polymer present in the plastic is dissolved in a solvent, allowing it to be separated and subsequently recovered in a pure form without altering its chemical nature. Organic recycling consists of a microbiological treatment of specific polymers that can be converted into stabilised organic waste, carbon dioxide, methane and water. This process requires the use of biodegradable plastic waste (Plastics Europe, 2021).

The most recycled plastics are PET, HDPE and PP. PET has a recycling rate of 50% and is usually recycled to make new PET bottles, backpacks and carpets. HDPE has a 30% recycling rate, with its main applications being non-food bottles, film-packaging and lawn products. PP has a significantly lower recycling rate, ranging from 1-3% in the US. This material is rarely recycled due to the difficulty of the process and since the financial investment is not always worth it. PVC plastics have a complex recycling process, that requires specialised infrastructure. LDPE, especially the plastic bags that use this type of plastic, tend to get stuck in the recycling machines which can damage it. Given its low cost and quality, it is often more economical to produce new LDPE rather than recycling it. PS plastics and those with recycling code number 7 are never recycled (Plastics For Change, 2022).

As final alternative, if recycling is not possible, the plastics are either converted into energy through incineration or transported to landfill (United Nations Environment Programme, 2021).

The price of virgin plastic is highly dependent on the price of oil and gas. It is therefore common to find a relationship between them. If the price of oil increases/decreases, it is expected that the price of plastic will also increase/decrease. On the other hand, the price of recycled plastic is more certain and does not vary as much with market fluctuations (Giustozzi & Yeong, 2021).

The prices for some resins for the year 2023 in Central Europe can be found in Figure 2.5.

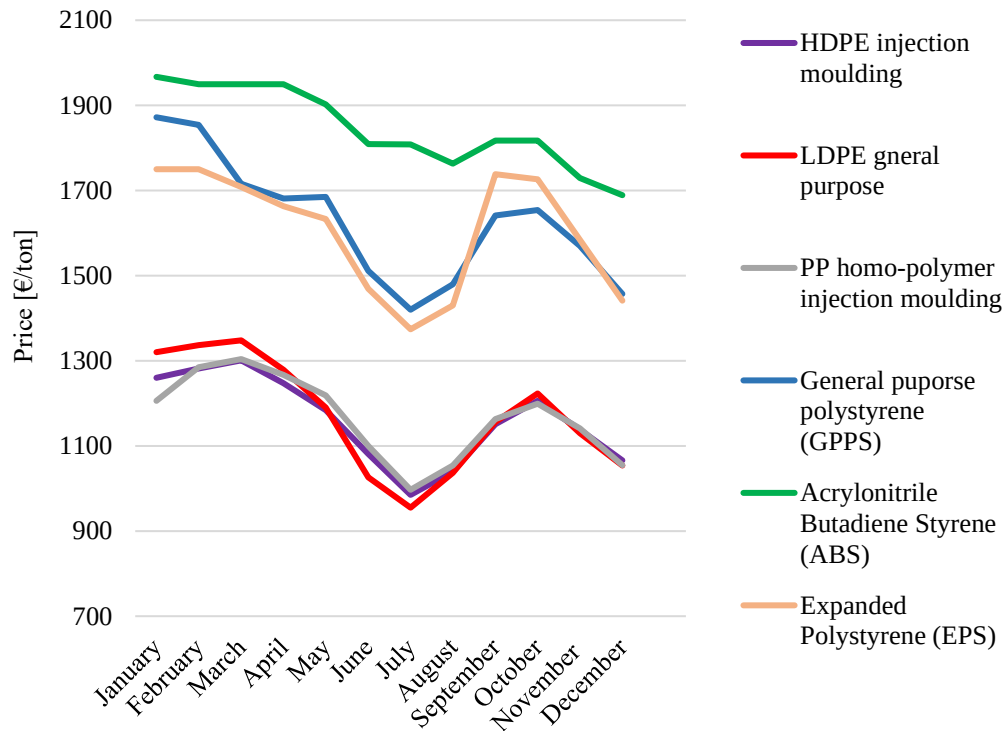


Figure 2.5 - Resins prices in 2023 (PlasticPortal.eu, 2024)

2.2.3 Environmental contamination

Between 1950 and 2017, an estimated 9.2 billion tonnes of plastic were produced. Of this amount, less than 10% was recycled and around 14% was incinerated (United Nations Environment Programme, 2021). The remaining amount was placed in landfills or released into the environment, including oceans. Plastics in the oceans can be found at all depths, from the surface to the seabed, and as mentioned by (Eunomia, 2016): “There is now on average an estimated 70 kg of plastic in each square kilometre of seabed”.

The impact that the production of plastic has must also be considered. Extracting oil and gas for plastic production results in the emission of greenhouse gases and other harmful substances into the atmosphere. Additionally, substantial amounts of wastewater, contaminated with oil and hazardous chemicals, are often released into the environment, posing risks to ecosystems (Bakas et al., 2021). The sticky nature of oil can physically harm animals whose habitats are near to oil extraction areas (El-Magd et al., 2023). Moreover, to emitting pollutants during the raw materials extraction, plastic production also releases toxic metals such as lead and mercury. The metals can subsequently contaminate flora, water and wildlife (Bakas et al., 2021).

Animals, particularly marine species, often mistake plastic and microplastic for food, which leads to their ingestion. Microplastics are particularly concerning because their small size allows them to enter the food chain at its earliest stages and accumulate in organisms consumed by humans, such as shellfish and fish (A. Khan et al., 2024). Plastics, including cigarette butts, plastic bottles, bottle caps, and plastic bags, are commonly found on both the surface and the ocean floor (Soares et al., 2020; United Nations Environment Programme, 2021).

Humans can meet these harmful agents through direct contact (skin, breathing), the food chain and the ingestion of microplastics (Emenike et al., 2023). The use of plastics can also lead to consumers being exposed to toxicity through the migration of particles, additives, impurities and chemicals degraded during the use of plastic. This exposure may result in health issues such as reproductive disorders, obesity, diabetes, asthma, cancer and antimicrobial resistance. It is estimated that the average person ingests the equivalent of a credit cards of plastic each week (Bakas et al., 2021; PlasticOceans, 2020).

Contact with plastic has also led to the death of millions of animals, mainly fish, marine organisms and birds. Many of these animals are facing extinction (Parker, 2019). Most of these deaths arise from entanglement and starvation (Puskic et al., 2024). In entanglement, the animal is trapped by a plastic bag, six-pack or other type of plastic that can prevent the animal from developing or moving. Often small particles of plastic, such as the ones resulted from degraded plastic bags, can be mistaken by the animals as food and the ingestion of the plastic gives the creatures a false sense of satiation, leading them to become malnourished and die. Creatures at the beginning of the trophic chain, such as plankton, also suffer the consequences of ingesting micro and nano-plastics which can affect their growth rate, as well as jeopardising the efficiency of photosynthesis, reproduction and survival (Parker, 2019; Soares et al., 2020).

Incinerating plastic, with or without electricity generation, also has an impact because the carbon and other chemical pollutants present in the plastic is released directly into the atmosphere in the form of carbon dioxide. Normally, the incineration of one tonne of plastic can generate up to 102000 microplastic particles and release 2.7 tonnes of CO₂. The environmental impact of the presence of CO₂ is already known and can lead to the formation of acid rain and the greenhouse effect, which consequently drives global warming (Bakas et al., 2021; Yang et al., 2021).

2.2.4 Use of plastics in construction

The use of plastics in construction has grown significantly in recent years, with applications ranging from insulation and pipework to window frames and interior design. In fact, construction is the second-largest industry for plastic use, following only the packaging industry. PVC is the most used plastic in this sector, making up 43% of its plastic consumption (Bakas et al., 2021).

The growth in the use of plastics is due to their characteristics, such as durability, resistance to corrosion, insulation, price-quality ratio, hygiene, fire, safety, easy installation, use and maintenance (Plastics Europe, 2023).

Some of the plastic products used are PVC pipes and window frames, expanded polystyrene and polyurethane as thermal and acoustic insulation, PVC membranes for terrace roof waterproofing, reo bar caps, rebar spacers, plastic formwork, safety fences, among others. Recycling these products can be more challenging as they are produced with the aim of lasting decades, unlike the plastic produced in packaging, which are intended for single-use and have a much shorter lifespan (Bakas et al., 2021).

Once the subject of recycling has been introduced, the use of recycled plastic in construction means that the challenges of achieving sustainability can be met. The use of recycled plastic is welcomed as the construction sector is one of the biggest users of raw materials. In order to utilise plastic waste, it is necessary to check if it meets requirements such as mechanical resistance, durability and cost-effectiveness (Awoyera & Adesina, 2020).

Some of the applications of plastic waste that have already been studied are:

- Utilizing LDPE waste plastic in flexible paver tiles shows that the tiles can endure significant bending, tensile and compressive forces, making them durable for outdoor applications and suitable for outdoor paving. LDPE also exhibits good resistance to weathering due to its low water absorption rate (Debele et al., 2024);
- The incorporation of plastic waste into concrete and mortar can enhance tensile and flexural strength, reduce water absorption, and lower the carbon footprint of construction materials (Awoyera & Adesina, 2020; Mohan et al., 2021). Plastic-modified concrete is lighter, which can improve seismic resilience and reduce labour costs (Awoyera & Adesina, 2020; Mohan et al., 2021). Additionally, plastic fibres improve abrasion resistance, making concrete more durable in high-wear applications (Mohan et al., 2021). However, challenges like weaker mechanical bonding can affect

compressive strength, although plastic fibres help mitigate crack propagation (Mohan et al., 2021);

- The incorporation of plastic waste in pavement base and sub-base layers enhances mechanical properties, including shear strength stiffness and bearing capacity, making pavements more durable and resilient under traffic loads (Awoyera & Adesina, 2020). Additionally, using various types of plastic in subgrade applications impacts geotechnical properties like compaction, California bearing ratio (CBR), permeability and resilient modulus (Abukhattala & Fall, 2021);
- The use of plastic waste into brick manufacturing can enhance sustainability and reduce environmental impact. While the addition of plastic waste decreases compressive strength and workability due to poor adhesion between materials, it significantly reduces water absorption, enhancing brick durability and longevity (Mohan et al., 2021). The use of plasticizers and finer particles can improve bonding and mitigate some of the negative effects on strength and workability (Mohan et al., 2021);

In developing countries, adobe or clay bricks are commonly used, as well as wood and bamboo. However, plastic waste can also be used, using various techniques. One of these techniques is the use of plastic bottles filled with sand. These can be grouped using some kind of mortar, leading to the formation of a wall (Plastics For Change, 2022).

Another method for constructing low-cost houses involves using plastic blocks designed to interlock, similar to Lego bricks. This allows the blocks to fit together without the need for cement (Bredenoord, 2017).

There are also companies like ByFusion which, the Figure 2.6 shows, convert plastic waste into blocks known as Replast. Although these do not have the same resistance as concrete, they have excellent characteristics for acoustic and thermal insulation (Idle, 2016). These can be in the form of retaining walls, acoustic insulation walls, shelters, fences, terraces and furniture (ByFusion, 2023).



Figure 2.6 - Use of replast on a wall (ByFusion, 2023)

2.3 Road pavements

Road pavements play a fundamental role in society by providing an important infrastructure for the economic, social and cultural development of a given region or country. They are essential for mobility, facilitating the transport of people and goods.

A pavement is a set of layers or stratum made of various materials supported by a foundation composed of natural soil that must be able to withstand the stress of vehicle wheels during its dimensioning period and the climate conditions of the area (Dhir et al., 2018). The number and size of its layers influence its behaviour (Bandeira, 2019). According to Infraestruturas de Portugal, the road network in Portugal in 2024 is 14.860 km long (Infraestruturas de Portugal, 2024).

The main functions of a pavement are:

- To provide a surface with adequate conditions for circulation, safety, comfort and economy (Instituto de Infra-Estruturas Rodoviárias IP, 2023) ensuring that the same conditions are maintained during the course of repeated passages of the vehicle's wheels during the dimensioning period. These conditions can include the coefficient of friction, waterproofing, polishing resistance, noise and vibration felt inside the vehicle (Mathew, 2009);
- Resisting and distributing the stresses of the expected traffic to the lower layers (Dhir et al., 2018);

- Protect the foundation from bad weather;
- Drain rain effectively, allowing vehicles to circulate safely;

The wide range of materials used in pavements can be grouped into the following groups:

- Soils;
- Coarse-grained crushed aggregate;
- Mixtures with bituminous binders;
- Mixtures with hydraulic binders;

For the top layers, mainly bituminous mixtures and mixtures with hydraulic binders can be used, leading to the formation of flexible, rigid or semi-rigid pavements.

Flexible pavements are the most common type found on roads. Its surface layers, surface course and eventually binder courses, are composed of bituminous mixtures. In situations where traffic is expected to be low, a surface treatment can be used on the surface course. In this type of pavement, it is usual for the surface layer to be the strongest and most resistant to withstand the highest levels of compressive stress (Instituto de Infra-Estruturas Rodoviárias IP, 2023).

Rigid pavements are used when a high volume of heavy vehicles is expected, such as roads near factories or harbours. The surface course of this pavement consists of a cement concrete slab. It tends to have a high flexural resistance and due to its greater rigidity, it distributes the vertical loads over a larger area. In order to prevent the concrete from cracking, it is often used short slabs or longitudinal steel reinforcement halfway up the slab (Instituto de Infra-Estruturas Rodoviárias IP, 2023).

Semi-rigid pavements are very similar in constitution to flexible pavements since their surface layers are made of bituminous mixtures. This construction solution is distinguished by the use of granular materials treated with hydraulic binders in the base layer (Instituto de Infra-Estruturas Rodoviárias IP, 2023).

2.3.1 Bituminous mixtures

The bituminous mixtures of flexible pavement are formed by combining bitumen with aggregates of various sizes. Bitumen, the primary component, is a black material consisting of hydrocarbons obtained from crude oil distillation in refineries. It is a viscoelastic, non-volatile,

and waterproof material. Its properties change based on the applied load and temperature (Brasileiro et al., 2019). At ambient temperatures, bitumen remains in solid state, while at higher temperatures, it transitions to a liquid or fluid state. Depending on their chemical composition, bitumen can be considered: saturated, aromatic, resinous and asphaltenes.

For bitumen to be used in pavements, it must fulfil certain conditions, such as:

- Ability to vary its consistency with temperature so that it can mix with aggregates at a high temperature and acquire stiffness at ambient temperature;
- The ability to mix with the aggregate to achieve a homogeneous mixture where there is a strong bond between the particles;
- Ability to guarantee the same characteristics throughout the dimensioning years, therefore being able to withstand the stresses to which it is subjected;

Some disadvantages of using bitumen in the bituminous mixtures of a pavement are:

- Degradation of the pavement due to oxidation effect (Gawande et al., 2012);
- Pathologies related to disaggregation of the aggregate to the bitumen (Gawande et al., 2012);
- Use of material from an oil product (Gawande et al., 2012).

To improve or modify the characteristics of bitumen, chemical agents can be used in the form of additives that will lead to the formation of a modified bitumen. Some of these additives can be natural rubber or tyre rubber, synthetic polymers such as Styrene-Butadiene-Styrene (SBS) and Ethylene-Vinyl Acetate (EVA) and some chemicals such as sulphur and amines.

The use of modified bitumen aims to:

- Reduce the thermal susceptibility;
- Increase flexibility and resistance to fatigue;
- Increase durability;
- Improve adhesion between aggregate and binder;

Typically, the layers used in a flexible pavement and their thickness will vary depending on the traffic expected for the pavement in question. They consist of a surface course, binder course, base course, sub-base course and foundation.

The topmost layer of pavement, known as the surface course, is particularly vulnerable to damage resulting from traffic and weather conditions (Instituto de Infra-Estruturas Rodoviárias IP, 2023). Consequently, it often requires the most significant investment for

maintenance (Gawande et al., 2012). For rigid pavements, a cement concrete slab serves as the surface course, while bituminous mixtures are employed for flexible pavements. In instances where traffic volume is low, a surface treatment can be utilized to establish the surface course. Given that this layer is in contact with the vehicle's wheels, it must ensure optimal comfort, traction (Bandeira, 2019), skid resistance (EAPA, 2023), and durability to ensure that the pavement remains unaffected during subsequent vehicle passes. Structurally, the layer must have the ability to withstand the loads imposed by vehicles and transmit them to the layers below. Additionally, it must be flexible enough to account for any settlement in the lower layers (Bandeira, 2019). Furthermore, it is crucial to ensure adequate impermeability to prevent pathologies in the lower layers and proper drainage to guarantee safe and unobstructed traffic flow. Table 2.2 shows some hot mix solutions adopted for the surface courses.

Table 2.2 - Usual hot mix surface courses (Estradas de Portugal 2009; Estradas de Portugal, 2014)

Layer	Description	Nomenclature
Surface Course	Bituminous Concrete	AC 14 surf binder (BB)
	Rough Bituminous Concrete	AC 14 surf binder(BBr)
	(micro) Rough Bituminous Concrete	AC 10 surf binder (mBBr)
	Bituminous drainage concrete	PA 12,5 binder (BBd)
	Bituminous concrete with hard aggregate encrustation	AC 14 surf binder (BB)
	Open bituminous mixture with modified bitumen with a high percentage of rubber	MBA-BBA
	Rough bituminous mixture with modified bitumen containing a high percentage of rubber	MBR-BBA
	Open bituminous mixture with modified bitumen with a medium percentage of rubber	MBA-BBM
	Rough bituminous mixture with modified bitumen containing a medium percentage of rubber	MBR-BBM

The binder course is used to improve the adhesion and transition between the surface course and the base course. It is especially used on pavements with high levels of traffic (Instituto de Infra-Estruturas Rodoviárias IP, 2023). It may not be necessary to use it when subjected to light traffic levels. Its main function is to guarantee stability and durability by

withstanding shear stresses imposed by the top layer (EAPA, 2023). Table 2.3 presents some of the hot mix solutions employed for the binder courses.

Table 2.3 - Usual hot mix binder courses (Estradas de Portugal, 2014)

Layer	Description	Nomenclature
Binder Course	Bituminous Macadam, Fuso A	AC 20 bin binder (MB)
	Dense Bituminous Mixture	AC 20 bin binder (MBD)
	High Modulus Bituminous Mixture	AC 16 bin binder (MBAM)
	Bituminous Concrete	AC 14 bin binder (BB)
	Bituminous Mortar with modified Bitumen	AC 4 bin binder (AB)

The base course serves as a structural layer and its composition varies depending on the type of pavement and traffic it is expected to handle. For flexible pavements, crushed granular materials are used, while uncrushed materials are suitable for light traffic, and granular materials treated with binders are preferred for high traffic (Instituto de Infra-Estruturas Rodoviárias IP, 2023). On the other hand, hydraulic binders are mixed with materials for rigid pavements, with uncrushed materials being used for light traffic and poor-quality concrete for heavy traffic. This layer is typically quite stiff (EAPA, 2023) and its main function is to provide fatigue resistance (EAPA, 2023) and mechanical strength to the pavement, allowing it to support and distribute the vertical loads of vehicles uniformly (Instituto de Infra-Estruturas Rodoviárias IP, 2023). This helps to prevent the underlying layers from being exposed to excessive stress and deformation (EAPA, 2023). Table 2.4 shows some hot mix solutions adopted for the base courses.

Table 2.4 - Usual hot mix base courses (Estradas de Portugal, 2014)

Layer	Description	Nomenclature
Base Course	Bituminous Macadam, Fuso B	AC 32 base binder (MB)
	Bituminous Macadam, Fuso A	AC 20 base binder (MB)
	High Modulus Bituminous Mixture	AC 20 base binder (MBAM)

The sub-base course is located below the base course and provides additional help to the upper layers in distributing loads. The constitution of this layer, regardless of the type of pavement, will depend on the volume of traffic applied and will be similar to the constitution

of the flexible pavement of the base course, but the materials tend to be of lower quality. In addition to its structural importance, this layer also serves to protect the lower layers during the construction phase, and protect the base course from capillary water rise and soil penetration (Bandeira, 2019). This layer also plays an active role in the internal drainage of the pavement (Bandeira, 2019).

The foundation is intended to serve as a base and provide support for the pavement. It is generally compacted natural soil, which can be local if it has characteristics that match the expected volume of traffic (Bandeira, 2019).

Figure 2.1 shows the cross-sectional profile of a pavement constituted by the various courses mentioned in this chapter.

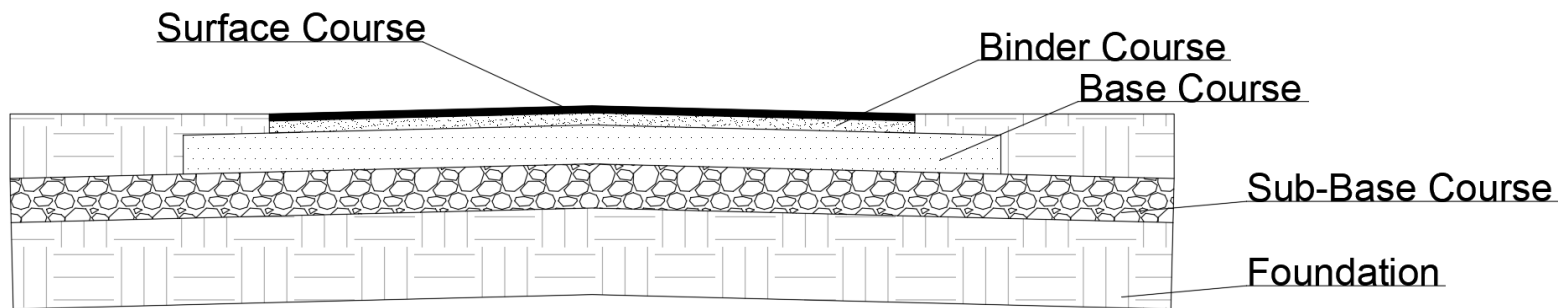


Figure 2.7 - Cross-sectional profile of a pavement

2.3.2 Techniques for producing bituminous mixtures

The techniques used for producing bituminous mixtures depend primarily on the production temperature and can be produced either in a central plant or in situ, depending on the project requirements. Hot bituminous mixtures (HBM) are the most widely studied and analysed technique for making these mixtures (Bandeira, 2019). It involves mixing different sizes of aggregate, filler, and bitumen at a high temperature, usually between 150 °C and 180 °C (EAPA, 2023). HBM is typically utilized to produce surface courses, binder courses and base courses, resulting in materials such as bituminous concrete, dense bituminous mix, and bituminous macadam.

Cold bituminous mixtures (CBM) are made using aggregates, fillers, bitumen emulsion, water and additives (Estradas de Portugal, 2014). Unlike HBM, this technique does not require heating the aggregate (Dash & Panda, 2018). Instead, bitumen is emulsified in water, and the resulting emulsion coats the aggregate, which then cures and gains resistance (EAPA, 2023). This type of mixture is recommended for roads with lower traffic and is commonly used

for pavement rehabilitation or maintenance such as patch repairs and crack sealing (EAPA, 2023; Dash & Panda, 2018). The use of CBM saves energy, is safer to apply, does not emit harmful gases and can be applied in any weather conditions (Dash & Panda, 2018). However, compared to hot bituminous mixtures, this type of mixture has some drawbacks such as lower stability and higher air voids. Additionally, research on CBM has been delayed (Dash & Panda, 2018).

Half warm bituminous mixture (HWBM) is produced with the same type of binder as CBM, but the aggregates are heated to a temperature between 70 °C and 100 °C (Bandeira, 2019; EAPA, 2023).

Warm bituminous mixture involves heating between temperatures of 100 °C and 150 °C. Depending on the desired properties, additional substances may be added (Bandeira, 2019). This type of mixture consumes less energy than HBM (EAPA, 2023), which leads to lower emissions of harmful gases, resulting in better working conditions for labourers (EAPA, 2023). This type of mixture allows full compatibility with RAP and less hardening of the bitumen (EAPA, 2023). Working at lower temperatures than HBM provides more time for transportation and compaction (EAPA, 2023).

2.3.3 Recycled materials in bituminous mixtures

Incorporating recycled materials into bituminous mixtures is a widely accepted practice. Various materials, including ashes, slags, oils, fillers and aggregates from quarry waste, tyre rubber, and concrete have been thoroughly tested and successfully integrated into bituminous mixtures. Table 2.5 showcases pertinent works of literature on the subject of recycled materials for use in bituminous mixtures.

Table 2.5 - Recycled materials in bituminous mixtures

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
Recycled Tyre Rubber		Small Particles	Not Specified	Not Specified	Not Specified	✓ More resistant to rutting and cracking.	(Willis et al., 2020)
		0.15 to 0.60	140 to 195	1.75 to 25% by weight of bitumen	Wet Method	✓ Lower penetration rate between 12 and 37%; ✓ Reduced ductility at 15 °C; ✓ Increased viscosity; ✓ Reduced phase angle; ✓ More resistant to rutting and cracking; ✓ Improved pavement performance and durability; ✓ Increased elasticity; ✓ More fatigue resistance.	(Brasileiro et al., 2019)
		0.6 to 3	Not Specified	1 to 10% of the total weight of the mixture	Dry Method	Not Specified	

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
Recycled Tyre Rubber		Not Specified	175	1.43% of the total weight of the mixture	Wet Method	✓ Increased viscosity; ✓ Increased coating of the aggregates; ✓ Good behaviour against moisture sensitivity; ✓ Improved elastic behaviour of the binder; ✓ Improved mixture fatigue performance; ✓ Good performance in terms of permanent deformation; ✗ Expensive Equipment; ✗ Instability when stored for more than 72h.	(Chavez et al., 2019)
		0 to 2	175	1.43% of the total weight of the mixture	Dry Method	✓ Improved mixture fatigue performance; ✓ Good performance in terms of permanent deformation; ✗ Long digestion times to achieve acceptable results.	(Chavez et al., 2019)
		Not Specified	175	2.38% of the total weight of the mixture as RAR	Semi-wet Method	✓ Resistance to water attack; ✓ Similar performance to wet process; ✓ No need for expensive material.	(Chavez et al., 2019)

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
Recycled Tyre Rubber		0.25 to 1	180	Up to 20% by weight of bitumen	Wet Method	✓ Higher rutting resistance; ✓ Better aging properties; ✓ Improved mixture fatigue performance; ✓ Higher resistance to the effects of high temperature; ✓ Reduced layer thickness; ✗ Expensive Equipment.	(Bressi et al., 2019)
		Not Specified	Not Specified	Not Specified	Dry Method	✓ Allows the use of coarser particles; ✓ Higher amount of rubber; ✓ Higher noise absorption; ✗ Low cohesion between rubber and bitumen; ✗ Higher moisture susceptibility; ✗ Higher detachment of aggregates.	
RAP		0.075 to 26.5	Not Specified	40% by weight of aggregate	Dry Method	✓ Decrease in mixing and compaction temperatures; ✓ Better volumetric properties than generic BM; ✓ Better performance properties than generic BM; ✓ Better Resistance to moisture; ✓ Better load spreading properties; ✗ Need to use a recycling agent.	(Pradyumna & Jain, 2016)

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
RAP		. Fine Fraction: 0 to 4.75; Medium Fraction: 4.75 to 12.5; .Coarsest Fraction: 12.5 to 19;	Not Specified	75% of the total weight of the mixture	Dry Method	✓ Costs reduction; ✓ Good in-service performance; ✓ Good high-temperature performance; ✓ No sensitivity to water damage; ✓ Able to regenerate and recover its properties; - X Complex conjugation of additives and rejuvenators.	(Antunes et al., 2023)
Slag	Steel Slag	. Ladle Furnace as fine aggregate and filler;	Not Specified	Not Specified	Dry Method	✓ Improved stability by 12%; ✓ Improved tensile performance by 6%; ✓ Good cohesion of the mixture; ✓ Polishing resistance within the reference; ✓ Good durability; ✓ Reduced water sensitivity; - X Greater void content; - X Requires a 15% higher volume of bitumen.	(Skaf et al., 2021)

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
Slag	Steel Slag	. Ladle Furnace as fine aggregate and filler; . Electric Arc Furnace as coarse aggregate;	Not Specified	100% by weight of aggregate	Dry Method	✓ Improved stability by 40%; ✓ Polishing resistance within the reference; ✓ Good durability; ✓ Reduced water sensitivity; - X Worst tensile performance by 25%; - X High porosity; - X Greater void content; - X Requires 35% higher volume of bitumen.	(Skaf et al., 2021)
	Furnace Slag	0 to 2	160	Not Specified	Dry Method	✓ Good adhesion with bitumen; ✓ Superior bitumen absorption; ✓ Excellent mechanical behaviour; ✓ Better thermal susceptibility; ✓ Better moisture susceptibility - X Greater void content.	(Skaf et al., 2016)
Recycled Concrete		Not Specified	Not Specified	Not Specified	Dry Method	- X Usable in low-volume roads; - X Lower quality than natural aggregates; - X Higher stripping potential; - X Lower water resistance; - X Requires a higher volume of bitumen.	(Pasandín & Pérez, 2015)

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
Recycled Concrete		Coarse aggregate: From 12.5 Fine aggregate: Up to 0.075	Not Specified	. From 20% to 100% as coarse aggregate .100% as coarse and fine aggregate;	Dry Method	✓ Better Marshall stability; ✓ Better fatigue performance; ✓ Better resistance to impact loading; ✓ Better polishing resistance; ✓ Skid resistance within the reference; - X Reduction in resilient moduli and indirect tensile strengths; - X Requires higher volume of bitumen; - X Exceeds the recommended OBC for mixtures with more than 60% of RCA.	(Nwakaire et al., 2020)
Stone Waste	Marble Wastes	0.074 to 19	Not Specified	100% by weight of aggregate	Dry Method	✓ Polishing resistance within the specification limits; ✓ Better Marshall stability; - X Aggregate impact value exceeds the limit; - X More suitable to be used in binder course; - X Usable in low and medium-volume roads.	(Akbulut & Gürer, 2007)
	Basalt Wastes	0.075 to 16	160 to 165	100% by weight of aggregate	Dry Method	✓ Material properties such as water absorption, polishing and stripping strength were within the limits; ✓ High Marshall stability.	(Karakuş, 2011)

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
Ashes	Fly ash from solid biomass combustion	From 0.125	Not Specified	5-10% of the total weight of the mixture	Dry Method	✓ Non-hazardous material; ✓ May be considered as an alternative to natural filler; - X Mill the ashes to obtain an adequate grading; - X Stiffens the bitumen excessively; - X May have leaching problems; - X High variability of ashes from the same power plants.	(Melotti et al., 2013)
	Municipal solid waste incineration ash (i) and Basic oxygen furnace slag (ii)	(i): <2.36; (ii): <13;	Not Specified	(i): 8 to 16% by weight of aggregate; (ii): 72 to 74% by weight of aggregate;	Dry Method	✓ Metal concentration leaching within the allowed values; ✓ High-temperature stability; ✓ High bearing capacity against load; - X Degrades the water damage resistance performance.	(Xue et al., 2009)
	Palm oil fuel ash	<0.075	Not Specified	1 to 4% by weight of aggregate	Bitumen Emulsion	✓ Lower voids content; ✓ Higher moisture damage resistance; ✓ Improved stiffness; ✓ Higher durability; ✓ Higher polishing resistance; ✓ Higher rutting resistance; - X Lower stability; - X Micro-crack development; - X Weak bonding between aggregate and binder.	(Usman et al., 2021)

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
Sulphur		Not Specified	145	20 to 50% by weight of bitumen	Wet Method	✓ Higher adhesion between the mixture particles; ✓ Lower voids; ✓ Higher toughness, rutting resistance and fatigue resistance.	(Nguyen & Le, 2019)
Bio-Oil	Wood and Paper industry	Not Specified	160	10% by weight of bitumen	Wet Method	✓ Lower aging rate; ✓ Higher resistance to cracking; X Higher rutting tendency.	(Ingrassia et al., 2020)
Waste limestone sludge		<0.075	162	4 to 8.5% by weight of aggregate	Dry Method	✓ Properties of a good filler such as fine nature, low active clay content and hydrophobic nature; ✓ Good bond with bitumen in the presence of water; ✓ Equivalent/Superior Marshall and volumetric properties; ✓ Higher cracking and rutting resistance; ✓ Good adhesion; ✓ Satisfactory performance against moisture; ✓ Superior load distribution characteristics; ✓ Higher fatigue resistance; ✓ Lower cost and greenhouse gas emissions.	(Choudhary et al., 2020)

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
Crushed Glass		<4.75	Not Specified	5 to 20% of the total weight of the mixture	Dry Method	✓ Improvement in the dynamic behaviour; ✓ Higher stiffness modulus; ✓ Higher internal friction; ✓ Less sensitive to temperature changes; ✗ Necessary to use lime to ensure strong cohesion between the glass and the stone; ✗ High smoothness of the glass particles does not let them absorb bitumen adequately.	(Arabani, 2011)
		<4.75	170	5 to 15% by weight of aggregate	Dry Method	✓ Higher Marshall stability; ✓ Stronger deformation resistance with the incorporation of lime; ✓ Less binder required; ✓ Good roadway reflection; ✓ Higher squid resistance; ✗ Weak binding strength between glass particles and bituminous mixture.	(Su & Chen, 2002)

Material	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
Powder	Recycled Concrete Aggregate	<1.18	Not Specified	5.1% by weight of aggregate	Dry Method	✓ Improve water sensitivity; ✓ Improve high-temperature properties; ✓ Improve fatigue life of the pavement;	(M. Chen et al., 2011)
	Recycled Brick Powder	<0.075	Not Specified	5% by weight of aggregate	Dry Method	✓ Better rutting resistance; ✓ Improve water sensitivity; ✓ Improve fatigue life of the pavement;	(M. Z. Chen et al., 2011)

2.4 Bituminous mixtures with plastics

The use of plastics in bituminous mixtures has been the subject of considerable interest due to the growing environmental problem of plastics and in improving road pavement properties. Various types of plastic, such as polyethene (PE), including high-density polyethene (HDPE) and low-density polyethene (LDPE), have been studied for their application in BM, followed by polyethene terephthalate (PET) and polypropylene (PP) (Willis et al., 2020). The choice of plastics is extremely important, preferably those with melting points between 110 °C and 160 °C (Remtulla et al., 2021), as this characteristic directly influences their appropriate incorporation into BM (Willis et al., 2020).

The soft nature of plastics makes them ideal for bitumen modification, as they melt and blend more easily, minimizing the risk of releasing chemical substances and microplastics into the environment (Remtulla et al., 2021). The size and shape of the plastic particles are also important, as large particles can jeopardize the workability of the bitumen and affect the mixing of the mixture and the gradation of the aggregates (Remtulla et al., 2021; Willis et al., 2020).

Experimental results have shown significant improvements when adding approximately 5 to 10% plastic in relation to the weight of bitumen (Government of India, 2019; Sasidharan et al., 2019), leading not only to a reduction in bitumen use (Bandeira, 2019; Gawande et al., 2012) but also increasing the maintenance period of modified roads compared to conventional ones (Sasidharan et al., 2019). Incorporating plastic into mixtures reduces the specific mass (Bandeira, 2019) and improves properties such as elasticity, adhesion, cohesion, stiffness, Marshall stability, resistance to polishing, permanent deformation and rutting (Giustozzi et al., 2022; Nouali et al., 2020; Willis et al., 2020).

In addition, bitumen modification reveals other factors such as lower penetration rate, higher softening temperature and increased resistance to temperature variations and damage caused by water and moisture (Chavan, 2013; Ranieri et al., 2017; Willis et al., 2020). However, there are risks associated with the inappropriate application of plastics in paving construction, such as the leaching of toxic components and the generation of dangerous chlorine-based gases (Sasidharan et al., 2019).

To benefit from the previously mentioned advantages, it is essential to avoid using PVC due to the release of dioxins and to keep the temperature below 180 °C during construction to avoid premature degradation and the release of harmful gases (Government of India, 2019). It is also important that the addition of plastics does not lead to a substantial increase in viscosity so that conventional pavement construction equipment can be used (Fang et al., 2014).

2.4.1 Dry method

The incorporation of plastics into bituminous mixtures can be done through the direct addition of polymers using the dry method. Recycled plastics can be introduced during the mixing phase or added to the hot aggregate in pellets or shredded form (Remtulla et al., 2021; Sasidharan et al., 2019). The plastic is added to the heated aggregate at around 170°C, and bitumen is then added to the mix at around 160°C (Gawande et al., 2012; Sasidharan et al., 2019). It is essential to mix the materials for a prolonged period to ensure complete fusion of the recycled plastic waste in the bituminous mix (Remtulla et al., 2021).

The volumetric characteristics of the plastic-modified bituminous mixture depend significantly on the shape and size of the plastic particles (Giustozzi et al., 2022). Generally, larger, more spherical, and fragmented plastic particles promote better compactability compared to fine, elongated, and flaky particles (Giustozzi et al., 2022). Ideally, the size of shredded plastic waste should be between 2-3 mm, ensuring better spreading and coating of the aggregate, with impurities not exceeding 1% (Sasidharan et al., 2019).

Recycled plastic waste can play various roles in bituminous mixtures, including modifiers, bitumen substitutes, coating, aggregate replacement, or a combination of previous roles depending on specific conditions and needs (Remtulla et al., 2021; Willis et al., 2020). The aggregate replacement approach is common for recycled plastics with a melting temperature higher than the production temperature of bituminous mixtures (Willis et al., 2020). This approach contributes to the structure of the aggregate by replacing part of the fine and/or medium particles (Willis et al., 2020). It is to take into account that the improvement in pavement characteristics is intrinsically related to the type of plastic used, as well as its size and shape (Giustozzi et al., 2022). To replace aggregate by recycled plastic, the plastic must undergo minimal processing to remain financially competitive with natural aggregates (Giustozzi et al., 2022).

For the dry process, it is essential to consider the melting temperature of the recycled plastic (Remtulla et al., 2021). Plastics with a melting point below the production temperature of the bituminous mixture can melt during mixing with the hot aggregates (Willis et al., 2020). This results in the formation of aggregates coated with a thin layer of plastic in the bitumen-aggregate contact zone, as shown in Figure 2.8 (Sasidharan et al., 2019; Willis et al., 2020). The introduction of plastics into the hot aggregates and the subsequent addition of the binder can seal the aggregates, giving them an oily texture, resistance to water absorption, and increasing their strength (Bandeira, 2019). This plastic coating on the stones improves the

surface properties of the aggregates, giving the mixtures greater stability (Koti Marg & Puram, 2013). The bond between the bitumen and the aggregates is considerably increased, resulting in better performance in terms of permanent deformation, thermal cracking, flexibility, and flexural strength of the surface layer (Bandeira, 2019).



Figure 2.8 - Aggregate coated with plastic (Radeef et al., 2022)

The dry method for incorporating plastics into bituminous mixtures is economically advantageous and logistically simpler for production in small quantities or in remote locations where bitumen modification facilities are scarce (Remtulla et al., 2021).

2.4.2 Wet method

When incorporating plastic via the wet method, plastic waste is melted and mixed with bitumen in specific proportions, as illustrated in Figure 2.9 (Gawande et al., 2012; Sasidharan et al., 2019), leading to the formation of modified bitumen (Ranieri et al., 2017; Willis et al., 2020). The aim is for the plastic to fuse completely with the bitumen to create connections with it (Remtulla et al., 2021). This modified bitumen mixture will then be added to the aggregates (Brasileiro et al., 2019). The interaction between the plastic polymers and the bitumen occurs through mechanical mixing at high temperatures for a certain period to promote physical and chemical interactions and also a homogeneous bituminous mixture (Brasileiro et al., 2019; Willis et al., 2020).



Figure 2.9 - Mixture between bitumen and plastic pellets (Giustozzi et al., 2022)

Plastics can be used in the form of flakes, pellets or powder (Giustozzi et al., 2022; Sasidharan et al., 2019). It is recommended to use recycled plastics with a low melting point, such as LDPE and HDPE (Willis et al., 2020), as these should have a melting temperature lower than the mixing temperature of the bitumen (Giustozzi et al., 2022). The dosage of plastic varies depending on the study and the desired characteristics but tends to be around 2 to 15% of plastic in relation to the mass of bitumen (Bandeira, 2019; Gawande et al., 2012; Sasidharan et al., 2019; Willis et al., 2020). The temperature range for this method varies, with some sources recommending a range between 155 °C and 165 °C (Sasidharan et al., 2019) while others suggest using temperatures above 160 °C (Giustozzi et al., 2022).

Recycled plastic waste fulfils various functions, such as binder extenders to compensate for part of the virgin bitumen in the mixture design, without necessarily providing a performance improvement, but to provide economic benefits or as binder modifiers to improve the properties of the bitumen (Giustozzi et al., 2022; Remtulla et al., 2021; Willis et al., 2020). Binder modification makes it possible to control the properties of the binder (Ranieri et al., 2017), making bitumen more rigid due to the reduction in the penetration index and less susceptible to thermal variations due to the increase in the melting point (Bandeira, 2019). In addition, there is a reduction in porosity, and a substantial increase in water resistance and modulus of rigidity (Bandeira, 2019).

Despite the benefits, the wet method is recognised for providing a more complete and reliable bituminous mixture compared to the dry method (Remtulla et al., 2021). However, it requires specialised mixing and storage facilities (Remtulla et al., 2021) and has poor storage

stability (Bandeira, 2019). It is essential to emphasise that not all polymers are suitable for these modifications, such as PVC, which tends to release toxic gases at high temperatures (Bandeira, 2019; Giustozzi et al., 2022). It is therefore necessary for plastics to be at least essentially free of impurities and foreign materials to guarantee the safety and effectiveness of the process (Giustozzi et al., 2022).

2.4.3 Semi-wet method

The semi-wet method is a specialized technique that has been developed to add materials like rubber (Chavez et al., 2019) as occurs in Reacted and Activated Rubber (RAR). This solution contains crumb rubber powder from used tyres with additives to apply directly into bituminous mixtures (Coll, 2013). In this method, the material undergoes prior treatment and digestion, similar to the wet method (Chavez et al., 2019). However, the material is added as another ingredient during the manufacturing process of the bituminous mixtures, just like the dry method (Chavez et al., 2019).

The semi-wet method involves incorporating the material into the bituminous binder in refineries or stationary bitumen terminals. Over time, the material is heated and melted, resulting in a modified bitumen binder. This binder is then transported to the hot bitumen mixing plant, where it is incorporated into the mixture (Picado-Santos et al., 2020). Digestion is carried out at a high temperature, usually around 160 to 210 °C (Quaresma et al., 2022).

The digestion time required for the semi-wet method varies according to the literature. According to (Chavez et al., 2019), the required digestion time is 30 minutes, which can be achieved during the transport of the mixture from the bitumen plant to the application site. However, another study (Quaresma et al., 2022) suggests that a digestion time of between 45 to 60 minutes is required. The digestion time is necessary to obtain satisfactory results such as resistance to water attack (Chavez et al., 2019).

By using the semi-wet method, the performance obtained through the wet method can be maintained without the need for specific equipment (Chavez et al., 2019).

2.4.4 Types of plastic already incorporated

The utilization of plastic in bituminous mixtures is becoming increasingly prevalent in modern times. This is not only done to enhance the properties of BM but also to mitigate the amount of plastic waste that exists. Current studies on this subject show various types of plastic, and often a combination of them. Almost all plastics undergo treatment before being

incorporated into BM, even if only to reduce their size. The size of plastic used is dependent on the purpose of the study and the type of material, with the dry method typically used for plastics possessing a high melting point and the wet method for those with a low melting point that can modify the bitumen. There are numerous advantages to using plastics in BM, including reduced need for bitumen (Bandeira, 2019), improved fatigue cracking resistance, greater rutting resistance, and enhanced water and humidity resistance. Further details on these findings can be found in Table 2.6.

Table 2.6 - Types of plastic incorporated in BM

Type of Plastic	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
PET	TLPP and VPP from PET bottles	Flake particles <10	Not specified	1 to 10% by weight of bitumen	Wet method	✓ Effective at high temperatures; ✓ Improved performance in cold climate regions; ✓ Improved fatigue cracking resistance; ✓ Higher stripping resistance; ✓ Higher adhesion between bitumen and aggregate; ✓ Higher Marshall Stability; ✓ High traffic volume and heavy vehicles; - X Lower rutting resistance.	(Gürü et al., 2014)

Type of Plastic	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
PET	Waste plastic bottle	0.425 to 1.18	157-162	2 to 10% by weight of bitumen	Dry method	✓ Higher fatigue resistance; ✓ Higher cracking resistance; ✓ Higher flexibility; - X Wet method is not possible due to the high softening point; - X Reduces the aggregate-bitumen adhesion at higher PET contents; - X Reduces the tensile strength at higher PET contents; - X Reduces the moisture resistance at higher PET contents; - X Stiffness reduction especially at higher PET contents.	(Modarres & Hamedi, 2014)
	Waste plastic bottle	<1.18	160±5	0 to 10% by weight of bitumen	Dry method - Added into the mixture in the last part of the mixing process and after adding and blending the binder with the aggregate.	✓ Higher resilient modulus; ✓ Higher stiffness; ✓ Higher permanent deformation resistance; ✓ Higher rutting resistance; ✓ Satisfy the standard requirements; - X Lower moisture resistance; - X Lower tensile strength ratio.	(Ahmadinia et al., 2012)

Type of Plastic	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
HDPE	Waste material	Powder particles <2	145 to 165	4 to 8% by weight of bitumen	Wet method	✓ Higher stability; ✓ Stronger than the control mix; ✓ Higher resistance to permanent deformation; ✓ Higher Marshall quotient; ✓ Higher stiffness; ✓ Higher ability to spread the applied load.	(Hinislioglu & Agar, 2004)
	Waste plastic from milk cartoons	2	Not specified	0.75 to 3% by weight of bitumen	Wet method	✓ Higher softening point; ✓ Higher stiffness modulus; ✓ Lower penetration value; ✓ Higher ability to spread the applied load at high temperatures; ✓ Higher shear resistance; ✓ Higher permanent deformation resistance; ✓ Higher fatigue life; ✓ Higher moisture resistance; ✓ Higher adhesion between aggregate and bitumen.	(Aschuri & Woodward, 2010)

Type of Plastic	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
HDPE	Hostel waste	0.3 to 4.75	Not specified	8 to 10% by weight of bitumen	Wet method	✓ Higher stability; ✓ Lower penetration value; ✗ Lower ductility; ✗ Higher flow values; ✓ Lower air voids; ✓ Higher Marshall quotient; ✓ Higher stiffness; ✓ Stronger than the control mix; ✓ Higher polishing resistance; ✓ Higher wheel loads; ✓ Higher durability; ✓ Lower cost.	(A. B. Khan & Jain, 2020)
PVC	Pipe waste	10 to 20	Not specified	<11% by weight of the total mixture	Semi-wet method	✓ Higher stiffness; ✓ Higher elasticity; ✓ Higher viscosity; ✓ Higher permanent deformation resistance; ✓ Higher durability.	(Abdel-Goad, 2006)
	Not specified	Not specified	160 to 170	0 to 6% by weight of bitumen	Wet method	✓ Lower penetration value; ✓ Higher kinematic viscosity; ✓ Improved flow, stability and density; ✓ Higher indirect tensile strength.	(Mohamady Abd-Allah et al., 2014)

Type of Plastic	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
LDPE	Plastic bags	2 to 5	170±10	0.5 to 0.9% by weight of bitumen	Wet method	✓ Lower penetration value; ✓ Improved shear resistance at medium to high temperatures; ✓ Higher softening point; ✓ Higher resistance to deformation; ✓ Lower temperature susceptibility; ✓ Better workability and compaction ability; ✓ Higher water resistance; ✓ Higher stiffness modulus; - X Poor storage stability at high temperatures; - X Poor compatibility between bitumen and plastic.	(Nouali et al., 2020)
	Plastic waste recycling factory	2 to 5	170	4 to 10% by weight of bitumen	Wet method	✓ Higher stability; ✓ Lower flow; ✓ Higher permanent deformation resistance; ✓ Resistant to high-traffic loading.	(Genet et al., 2021)

Type of Plastic	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
PP	Not specified	Not specified	160 to 190	0.5 to 11% by weight of bitumen	Wet method	✓ Lower penetration value; ✓ Higher softening point; ✓ Improvements of complex modulus and phase angle properties at low frequency and high temperature; ✓ Higher permanent deformation resistance; ✓ Higher durability; ✗ Higher viscosity; ✗ Poor storage stability; ✗ Lower ductility.	(Brasileiro et al., 2019)
	Covid-19 plastic waste	50 to 80	165 to 175	10 to 20% by weight of bitumen	Wet method	✓ Volumetric and Marshall properties of the mix within the limits; ✓ Higher Marshall stability; ✓ Increase in penetration, softening point and specific gravity; ✓ Lower flow.	(Dadwal et al., 2021)

Type of Plastic	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
PS	Recycled PS from Hangers; Recycled High Impact PS; General Purpose PS;	Not specified	Not specified	1 to 2% by weight of the total mixture	Dry method	✓ Higher rutting resistance; ✓ Higher stiffness in temperate conditions; ✓ Higher deformation resistance; ✓ Higher durability; - X Low cohesion with 2% of PS; - X Higher percentage of voids; - X Lower cracking resistance in cold regions; - X Processed plastic.	(Vila-Cortavitate et al., 2018)
EVA	Not specified	Not specified	150 to 190	1 to 8% by weight of bitumen	Wet method	✓ Lower penetration value; ✓ Higher softening point; ✓ Higher complex modulus; ✓ Higher rutting resistance at high temperatures; ✓ Higher storage stability; - X Higher viscosity; ✓ Higher ductility values; ✓ Lower phase angle.	(Brasileiro et al., 2019)

Type of Plastic	Origin	Particle Size [mm]	Mixing Temperature [°C]	Incorporation Rate	Technique	Observations	References
EVA	Plastic Waste	<4	160	5% by weight of bitumen	Wet method	✓ Higher stiffness; ✓ Higher elasticity; ✓ Lower phase angle; ✓ Higher water resistance; ✓ Good interaction between plastic and bitumen due to its lower melting point; ✓ Higher fatigue resistance than the dry method; ✓ Higher rutting resistance.	(Ranieri et al., 2017)
		<4	180		Dry method	✓ Higher water resistance than the wet method; ✓ Higher stiffness than the wet method; ✓ Higher fatigue resistance; ✓ Higher rutting resistance.	

2.4.5 Advantages and disadvantages of incorporating plastics

The incorporation of plastics into bituminous mixtures has attracted significant research interest, primarily focused on two key methodologies: the wet and dry methods. A more recent approach, the semi-wet method, has received comparatively less attention in studies. Research into these methods has highlighted various advantages and disadvantages, each with distinct implications for their efficiency, operational feasibility, and environmental impact.

Predominantly favoured in literature, the wet method constitutes over 60% of recycled plastics used in bituminous mixtures (Willis et al., 2020). This method offers significant advantages, such as enhancing the flexibility and longevity of resulting mixtures (Chavez et al., 2019; Gawande et al., 2012). Studies demonstrate a substantial increase in Marshall stability, two to three times greater than reference bitumen (Gawande et al., 2012; Sasidharan et al., 2019). In addition, it has been observed that BM with this method has been able to withstand adverse conditions underwater for prolonged periods (Gawande et al., 2012). The wet method also accommodates the recycling of diverse types, sizes and shapes of plastics and rubber waste (Gawande et al., 2012). The incorporation of recycled plastic provides a hardening effect on bitumen, increasing its stiffness, polishing resistance, rutting and indirect tensile strength (Bressi et al., 2019; Sasidharan et al., 2019; Willis et al., 2020). However, this method requires specific and expensive equipment for bitumen modification, consumes more time and energy, and may encounter instability issues during long-term storage, potentially resulting in phase separation and a heterogeneous bitumen composition (Brasileiro et al., 2019; Chavez et al., 2019; Gawande et al., 2012; Ranieri et al., 2017). Additionally, there are limitations on the maximum percentage of plastic waste that can be incorporated (Gawande et al., 2012), and high temperatures can increase pollutant emissions, which negatively impacts the environment and workers' health (Willis et al., 2020).

The dry method offers a simpler alternative, eliminating the necessity for specialised equipment to modify the bitumen (Brasileiro et al., 2019; Ranieri et al., 2017). In this method, coating the aggregates with plastic significantly improves the quality of the aggregate, reducing moisture absorption, and increasing water resistance, polishing resistance and hardness (Bandeira, 2019; Gawande et al., 2012; Willis et al., 2020). Consequently, resulting mixtures exhibit enhanced resistance to rutting (Willis et al., 2020) and increased bitumen bonding (Gawande et al., 2012). Theoretically, the amount of plastic that can be incorporated via the dry method is greater than in the wet method (Giustozzi et al., 2022; Giustozzi & Yeong, 2021),

resulting in a more cost-effective bituminous mixture (Bandeira, 2019). However, this method is limited to waste plastic materials and may require long digestion times for acceptable results (Chavez et al., 2019; Gawande et al., 2012). Nevertheless, it is important to highlight the lack of cohesion between the polymer and bitumen, which may lead to increased susceptibility to moisture and aggregate detachment (Bressi et al., 2019).

The semi-wet method maintains the advantages of the wet method while mitigating or eliminating its operational disadvantages (Chavez et al., 2019). This method sustains the performance achieved through the wet method without the necessity for specific equipment, requiring minimal interventions compared to the wet method (Chavez et al., 2019).

2.5 Final considerations

The information presented above highlights the complexity and relevance of the issues surrounding plastics and road pavements.

Plastics are widely used due to their versatility, but their mass production and improper disposal can have severe environmental consequences. Proper management and recycling can help alleviate these impacts, but recycling faces challenges in terms of efficiency and economic feasibility.

Road pavements are crucial for mobility and socio-economic development, but they face difficulties in finding more durable, economical, and eco-friendly solutions. Recycled materials, including plastics, can enhance road durability and mechanical properties, but their selection, application methods, and environmental considerations must be carefully balanced to ensure effectiveness and sustainability.

Both themes emphasise the need for innovative approaches, sustainable technologies, and public awareness. Reducing the consumption of single-use plastics, developing alternative materials, and promoting sustainable practices in road paving are critical steps towards a more sustainable future. By doing so, we can safeguard natural resources for future generations. Materials and methods

3 Materials and methods

As an innovative experimental procedure, the first step was to analyse the types of plastic and their suitability for wet and dry incorporation. After selecting the most favourable type of plastic and incorporation method, tests were carried out to determine the optimum bitumen content and performance of the mixture studied. For the water sensitivity, permanent deformation, stiffness modulus and fatigue tests, the results are compared with a reference mixture AC 14 35/50, allowing the results obtained to be compared more efficiently.

The flowchart in Figure 3.1 summarises the various tests that were carried out.

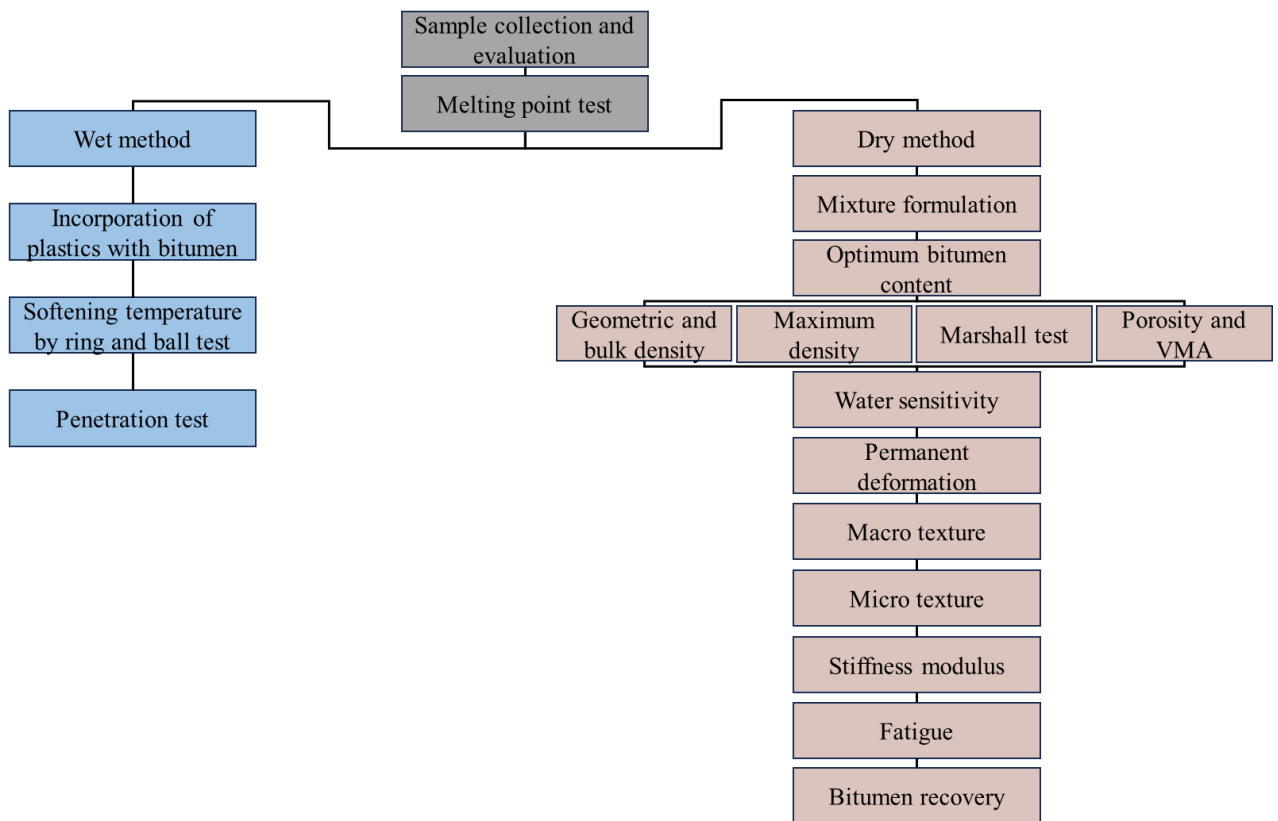


Figure 3.1 - Flowchart with tests carried out

3.1 Sample Collection

In order to acquire samples that would allow the investigation of this subject, a visit was performed to a waste treatment centre of Seixal. The aim was to select samples of non-recyclable plastics, where their only destinations were essentially landfills or incineration for electricity production.

From the samples selected and collected, it was only possible to obtain a brief description of them, according to the supplier's designation:

- Sample A - Plastics and rubbers 10-30;
- Sample B – Rejected Aluminium capsules;
- Sample C – Plastics washing machines 10-30, flotation 4;
- Sample D – PS/ABS refrigerators (PS2);
- Sample E – Rejected aluminium cans, light flotation 4;
- Sample F – Plastics refrigerators, light flotation 2;
- Sample G – HDPE boxes;
- Sample H – Polyurethane refrigerators;
- Sample L – Plastic pallets;
- Sample J – SDAS, light flotation 2.

Note: The samples collected can be seen in Figure 3.2. However, as they are the central theme of this research, the different samples will also be presented individually in the annexes section, between Figure A.1 and Figure A.1.10.

Of the samples collected, six had heterogeneous characteristics and the others had homogeneous characteristics. Furthermore, only sample “G” has commercial value. The next items will present the performed tests.

Sample A



Sample B



Sample C



Sample D



Sample E



Sample F



Sample G



Sample H



Sample L



Sample J



Figure 3.2 – Sample collection

3.2 Sample evaluation

The first step of the study began by evaluating each sample. Therefore, the following steps were followed:

1. Selection of a portion of the sample;
2. Photographic registration;
3. Weighing;
4. Visual separation of the various plastics present in the sample*;
5. Weighing and photographic registration of the various plastics*;
6. Determination of the percentage of each plastic present*;
7. Selection of the most representative plastics and/or those with possible better characteristics*;
8. Density test using a bucket of water to separate the plastics selected in step “7” dividing them into floating and non-floating*;
9. Weighing and photographic registration of the floating and non-floating plastics*;
10. Determining the percentage of each plastic present in the sample*;
11. Repeat step “7”.

*: Procedure adopted only for heterogeneous samples.

With this process it was possible to get a clearer idea of the constitution of each sample, allowing to choose the most representative elements of each sample. After the separations, a total of 75 samples were obtained.

3.3 Melting point test

The next step was to determine the melting point of each sample, to assess the capacity of plastics to be incorporated by wet method (incorporation in bitumen to modify it and/or function as a binder extender). Although it is known that a greater quantity of plastic waste can be incorporated using the dry method, since this investigation involves a material that has never been incorporated into bituminous mixtures, it is logical to explore whether it can be incorporated through the wet method.

In sample A all constituents were submitted to the melting temperature test, regardless of whether they were plastic or not. As an example, fabrics, wood and paper were used.

In the subsequent samples, only the most representative elements and/or those with the best characteristics were submitted to the melting temperature test.

To be noted that harmful elements, such as PVC, were not considered in this test, since chloride components can be emitted during the heating process.

To proceed with the melting temperature test, the following steps were adopted and developed throughout the experimental study:

1. Placing a sample of the selected plastics in a ventilated oven at 50 °C for approximately 45 minutes;
2. Weighing and photographic registration of the various samples;
3. Repetition of steps “12” and “13” for temperatures of: 75 °C, 100 °C, 110 °C, 120 °C, 130 °C, 140 °C, 150 °C, 160 °C, 170 °C, 180 °C, 190 °C and 200 °C.

It was verified that the particles with lower density (less than 1g/cm³) melted at lower temperatures. Photographic records are present from Figure A.3.1 to Figure A.12.6.

3.4 Incorporation of plastics with bitumen

The samples with lower fusion temperatures and more homogeneous were selected to proceed with the second test.

In this test, it was intended to determine the behaviour of the selected samples with a 35/50 bitumen. It is intended that the bitumen used contains 50 g of mass at a temperature of 150 °C.

The laboratory procedure took the following steps:

1. Placing the bitumen in an oven;
2. Separation and weighing of the desired sample so that it contains 1% of the mass of the bitumen;
3. Repeating step “2” to obtain a set of containers with 1% plastic by bitumen mass until a total of 20%;
4. Remove 50g of the bitumen heated in an oven;
5. Place the bitumen on a heating plate to minimize its temperature losses;
6. Add a sample with 1% of the bitumen mass and stir this for approximately 30 seconds;
7. Repeat step “6” to obtain the concentrations of 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10% of the bitumen mass;
8. Place the mixture in an oven at 150 °C for approximately 30 minutes;

9. Remove the mixture from the oven and place it on the heating plate;
10. Photographic registration;
11. Stir the mixture for approximately 30 seconds;
12. Repeat step “6” for 11% to 20% of the bitumen mass;
13. Place the mixture in an oven at 150 °C for approximately 30 minutes;
14. Stir the mixture for approximately 30 seconds and photographic registration;
15. Place the mixture in an oven at 150 °C for approximately 60 minutes;
16. Stir the mixture for approximately 30 seconds and photographic registration;
17. Place the mixture in an oven at 180 °C for approximately 90 minutes;
18. Stir the mixture for approximately 30 seconds and photographic registration.

Photographic records are present from Figure A.13.1 to Figure A.13.4.

3.5 Preparation of samples for softening temperature and penetration test

To carry out the above tests using virgin bitumen and bitumen with 1%, 2%, 4% and 6% plastic, for a 50/70 bitumen. It was necessary to create samples containing the desired percentages of plastic. The plastic was cut manually using scissors and incorporated with the bitumen at 150°C, and after 90 minutes in a ventilated oven at 150°C none of the samples showed any signs of being incorporated with the bitumen. Not reflecting the results observed in section 3.3.

Then the plastic was mixed again with a bitumen now at 175 °C, and after 90 minutes in a ventilated oven at 175 °C, the results were still not intended.

Expecting that a size reduction would improve the results obtained, an industrial shredder from a waste centre was used to obtain plastic particles between 5 and 10mm in size. After the incorporation attempt, the problem with the partially melted bitumen remained.

Therefore, it was not possible to obtain a homogeneous mixture for the softening temperature by ring and ball test and for the penetration test.

Anyway, the tests were done with the samples of virgin bitumen and bitumen with 1%, 2%, 4% and 6% of plastic incorporated at 175 °C for 90 minutes.

3.6 Softening temperature by ring and ball test

This test was carried out following standard EN 1427 (CEN 2010b) and aims to determine the softening temperature of bitumen and bituminous binders, in the temperature range between 28 °C and 150 °C.

The softening temperature corresponds to the average of the temperatures at which the two samples soften enough to allow the respective balls to pass through them and descend wrapped in bitumen.

A 50/70 bitumen will be used. This test will be performed for virgin bitumen and bitumen with 1%, 2%, 4% and 6% plastic. Figure 3.3 shows the softening temperature by ring and ball test in progress.



Figure 3.3 - Softening temperature by ring and ball test

3.7 Penetration test

This test was carried out accordingly EN 1426 (CEN 2015) and aims to determine the consistency of bitumen and binders.

Consistency is expressed as the depth, in tens of millimetres, to which a needle penetrates the material under specified conditions of temperature, load and duration of load application.

A 50/70 bitumen will be used. This test will be performed for virgin bitumen and bitumen with 1%, 2%, 4% and 6% plastic. Figure 3.4 shows the equipment needed for the penetration test.



Figure 3.4 - Penetration test equipment

3.8 Incorporation of plastics by dry method

Since it was not possible to obtain a homogeneous mixture by the wet method, the plastic will be incorporated by the dry method. This test will evaluate the results obtained with the plastic added to the overheated aggregates at 200 °C. The bitumen will be added later at 175 °C, obtaining a mixing temperature usually between 160 and 175 °C.

A 1200g Marshall specimen will be created using a 90%-10% aggregate-to-plastic ratio. An AC-14 formulation with a bitumen content of 4.5% will be used.

Table 3.1 shows the material quantities for the Marshall specimen with 4.5%.

Table 3.1 - Marshall specimen with 4.5% bitumen

Material	Quantity [g]
Bitumen	51.7
Basalt 10/16	275.6
Basalt 4/12	378.9
Limestone 0/4	218.2
Basalt 0/4	126.3
Commercial filler	34.4
Plastic	114.8

The laboratory test will follow the following steps:

1. Weighing of each aggregate and plastic;

2. Placing the aggregate in a ventilated oven for 3 hours at 200°C;
3. Place the heated aggregate and cold plastic in the mixer;
4. Mix the aggregate and plastic for 2 minutes;
5. Add the bitumen at 175°C;
6. Mix the mixture for 3 minutes;
7. Place in Marshall test mould;
8. Place in a device that gives 75 blows on each side of the specimen;
9. Wait for the specimen to cool down before demoulding.

Figure 3.5 shows the main steps mentioned above.

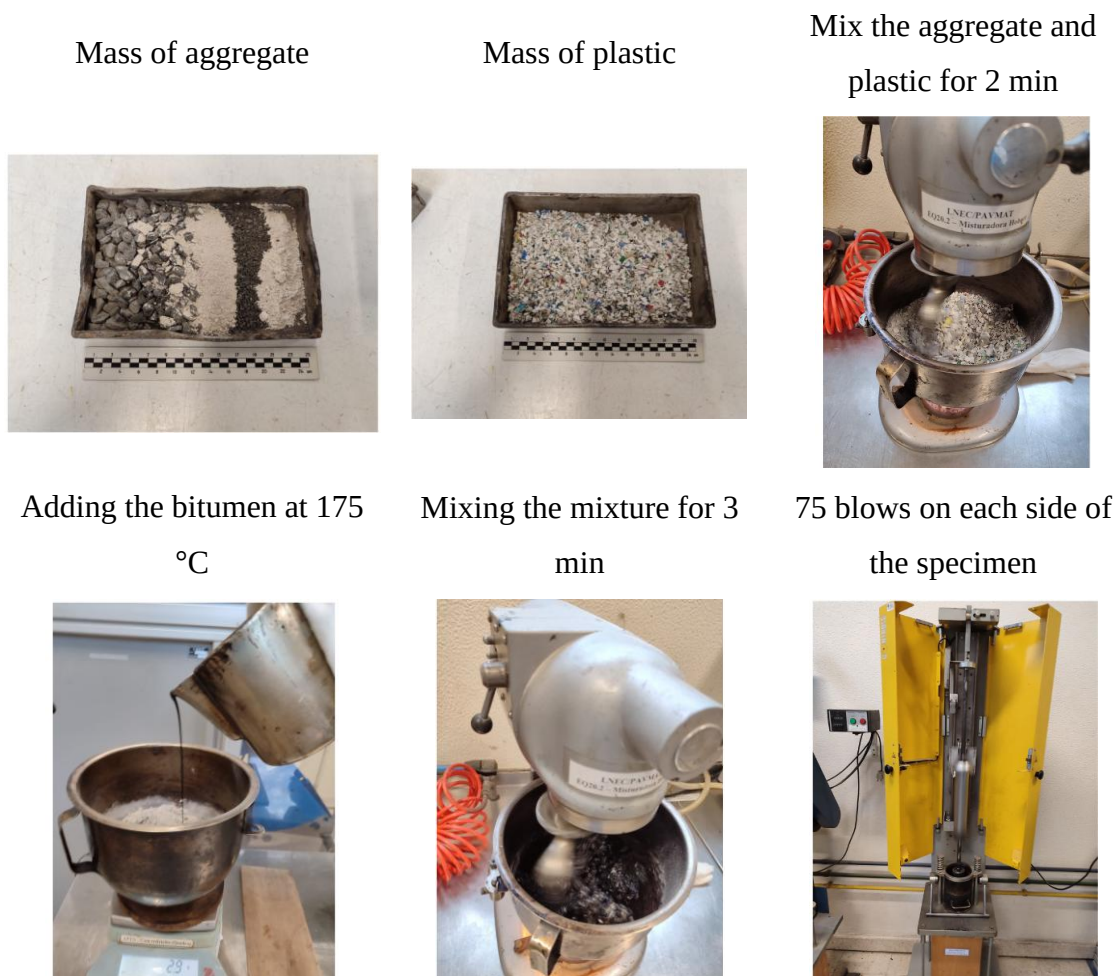


Figure 3.5 - Dry method – methodology

3.9 Optimum bitumen content

To determine the optimum bitumen content, twelve Marshall specimens were made. Each of the three bitumen contents to be analysed – 3.5%, 4% and 4.5% - had four samples

made. The specimens were calculated with 1080g of mass, to obtain the dimensions within the limits required for the Marshall tests carried out afterwards. After the specimens were made, various tests were conducted to achieve the desired OBC. Table 3.2 shows the tests that were performed.

Table 3.2 - Optimum bitumen content tests

Scope (Standard)	Description	Results
Geometric density	Relationship between apparent mass and volume of a given set of aggregates.	Table A.14
Bulk density EN 12697-6 (CEN 2020)	Determine the mass per unit of volume, including the air voids of a bituminous mixture.	Table A.15
Maximum density EN 12697-5 (CEN 2018)	Determine the mass per unit of volume without the air voids of a bituminous mixture.	Table A.16
Marshall test EN 12697-34 (CEN 2020)	Determine the stability, flow and Marshall quotient values of a bituminous mixture.	Table A.17
Porosity	Volume of air trapped between the aggregate and bitumen particles of a mixture.	Table A.18
Voids in the mineral aggregate (VMA)	Volume of intergranular voids between particles of the compacted bituminous mixture, which includes the porosity and the bitumen volume of the mixture.	

The specimens were made using the methodology presented in chapter 3.7.

Table 3.3 shows the quantity of materials used to make the specimens.

Table 3.3 - Materials used to make the Marshall specimens

Constituents [g]	Bitumen content [%]		
	3.5	4.0	4.5
Bitumen	36.5	41.5	46.5
Basalt 10/16	250.4	249.2	248.0
Basalt 4/12	344.3	342.7	341.1
Calcareous 0/4	198.3	197.3	196.4
Basalt 0/4	114.8	114.2	113.7
Commercial filler	31.3	31.2	31.0
Plastic	104.3	103.8	103.3
Total	1080.0	1080.0	1080.0

3.10 Water sensitivity

This test was carried out accordingly EN 12697-12 (CEN 2018) by method A and aims to determine the water sensitivity of specimens of bituminous mixtures.

3.11 Wheel tracking

This test was carried out accordingly EN 12697-22 (CEN 2020) aims to determine the susceptibility of bituminous materials to deform under load.

The wheel tracking test will require:

- Two slabs with the bituminous mixture under study with dimensions of 305x305x50mm³;
- Wheel tracking device (small size device);

3.12 Macrotexture

Macrotexture tests on BM by EN 13036-1 (CEN 2010a) have the function of evaluating the surface characteristics of the pavement, which are essential for guaranteeing the safety and functional performance of pavements. The test performed was the determination of the average macrotexture depth and was following EN 13036-1.

3.13 Microtexture

Microtexture test on BM has the function of evaluating the skid resistance of the pavement surface. The test performed was the determination of the skid resistance by the Pendulum test according to EN 13036-4 (CEN 2011a).

3.14 Stiffness modulus

The test carried out was the four-point bending test (4PBT) following standard EN 12697-26 (CEN 2028b). This test aims to measure the stiffness of bituminous mixtures. The tests involve prismatic specimens subjected to four-point periodic bending with free rotation and horizontal translation at all load and reaction points.

The complex stiffness modulus $[E^*]$ obtained from the 4PB test shown in Equation (3.1), is made up of two components, the real component $[E_1]$ represents the energy stored in the material or rigidity of the material and the imaginary component $[E_2]$ represents the energy dissipation or viscous behaviour of the material, the latter being obtained from Equation (3.2) and (3.3) respectively.

$$E^* = |E^*| \times (\cos(\phi) + i \times \sin(\phi)) \quad (3.1)$$

$$E_1 = |E^*| \times \cos(\phi) \quad (3.2)$$

$$E_2 = |E^*| \times \sin(\phi) \quad (3.3)$$

The phase angle $[\phi]$ indicates the phase difference between the applied stress and the resulting deformation. It quantifies the ratio between the elastic and viscous properties of the material. A ϕ of 0° signifies purely elastic behaviour, while a ϕ of 90° degrees signifies purely viscous behaviour. It can be obtained using Equation (3.4):

$$\phi = \arctan\left(\frac{E_2}{E_1}\right) \quad (3.4)$$

The stiffness modulus $[E]$ can be calculated by Equation (3.5):

$$E = \sqrt{E_1^2 + E_2^2} \quad (3.5)$$

Materials with high stiffness modulus, they exhibit greater rigidity, resulting in less deformation under an applied load and minimal elastic deformation, signifying their ability to withstand high loads without experiencing significant deformations. Conversely, materials with

lower stiffness modulus are less rigid, making them more prone to deformation under an applied load and demonstrating greater elastic deformation. This suggests that they are more flexible and can endure deformation before failing.

3.15 Fatigue

The fatigue test was performed using the four-point bending test (4PBT) with controlled extension mode according to standard NP 12697-24 (CEN 2018a). This test aims to assess the reduction in material strength under repeated loads compared to that under a single load. The test simulates repeated loading through cycles, representing the application and removal of a cyclic load. This mimics real-world usage conditions where the material is subject to repeated loads over time.

The extension $[\varepsilon]$, indicates the reaction of the mixture to the applied load. Higher values of extension tend to indicate greater deformation, which can lead to earlier failure.

The number of cycles $[N]$ represents the number of times the load is applied to the bituminous mixture before failure occurs. A higher number of cycles to failure indicates greater fatigue resistance.

The fatigue law describes the relation between strain and the number of load cycles at failure. The strains considered were: ε_4 for 10,000 cycles, ε_5 for 100,000 cycles and ε_6 for 1,000,000 cycles. The fatigue law can be calculated using Equation (3.6):

$$\varepsilon = k_1 \times N^{k_2} \quad (3.6)$$

Where k_1 and k_2 are coefficients of the strain fatigue law.

3.16 Bitumen recovery

This test was initially carried out following NP EN 12697-3 (CEN 2018c) and then using an internal procedure. This procedure aims to recover the bitumen from the bituminous mixture, to evaluate its properties, namely to understand what condition it is in and whether or not it has been modified by the plastic.

The materials needed to carry out the internal test are:

- Bituminous mixture;
- Toluene;
- Centrifuge;

- Rotary evaporator;

The internal procedure was carried out as follows:

1. Place the BM in a centrifuge with toluene for about 1 hour;
2. Remove the liquid (toluene, bitumen and fine aggregates) and place in a centrifuge to remove the fine aggregates;
3. Place the liquid with only toluene and bitumen in a rotary evaporator system until all toluene has been evaporated. A pressure of 300 ± 5 mbar and a temperature of 110 ± 5 °C were used;
4. After evaporating the toluene, the temperature was increased to 160 ± 5 °C and the pressure was changed to 80 ± 5 mbar;

Figure 3.6 shows the process part of the toluene evaporating using the rotating evaporation system.



Figure 3.6- Bitumen recovery

4 Presentation and discussion of results

This chapter presents the results and analysis of the various laboratory tests outlined in Chapter 3. In the water sensitivity, wheel tracking, stiffness and fatigue tests, the performance of the bituminous mixture under investigation is compared with that of the reference mixture, AC 14 surf 35/50.

4.1 Sample evaluation

Based on the methodology used to separate and evaluate the 10 samples studied, it is possible to conclude that:

- Sample A shows a very heterogeneous sample where rubbers, white plastics and black plastics predominate. The percentage of each constituent can be seen in Figure A.2.1;
- Sample B is a heterogeneous sample with 10 or so constituents, where aluminium, mixed paper caps and white and blue capsules predominate. The percentage of each constituent can be seen in Figure A.2.2;
- Sample C is a heterogeneous sample with 9 constituents, where white, grey, transparent and black plastics predominate. The percentage of each constituent can be seen in Figure A.2.3;
- Sample D is a homogeneous sample with thermoset-type plastics;
- Sample E is the most heterogeneous sample of all with 20 different constituents. The percentage of each constituent can be seen in Figure A.2.4;
- Sample F presents 16 constituents, where rigid white plastic predominates with a representation above 50%. The percentage of each constituent can be seen in Figure A.2.5;
- Sample G is a homogeneous sample consisting of HDPE;
- Sample H is a homogeneous sample consisting of polyurethane;
- Sample I is a plastic taken from a pallet;
- Sample J is a heterogeneous sample with 11 constituents where rigid black plastic and rigid white plastic predominate. The percentage of each constituent can be seen in Figure A.2.6.

4.2 Melting point test

Following the analysis of the behaviour of the various constituents of the samples across different temperatures, the following conclusions can be drawn:

- Out of 16 constituents tested in sample A, only the floating part of the transparent plastics melted at a temperature of around 150 °C, resulting in the melting of just 2.5g within a sample weighing approximately 1068g mass. Leading to only 0.23% of the sample showing promising characteristics. Therefore, this sample will not be considered for the following tests. Their constituents and their melting points can be seen in Figure A.3.1 to Figure A.3.25;
- In sample B, it was concluded that the mixed floating paper capsules, the blue capsules, the white floating capsules and the transparent floating plastics melted at a temperature of approximately 120 °C, resulting in approximately 77% of the sample showing promising characteristics for further testing. Their constituents and their melting points can be seen in Figure A.4.1 to Figure A.4.13;
- In sample C, the floating transparent plastics were the only ones to melt at a temperature of approximately 180 °C, corresponding to about 8% of the sample. The results of this sample did not show promising characteristics for the following tests. Their constituents and their melting points can be seen in Figure A.5.1 to Figure A.5.8;
- The sample D did not melt when exposed to 200 °C. This concludes that the sample appears to be interesting if the incorporation of plastics through the dry method is chosen. Their constituents and their melting points can be seen in Figure A.6.1;
- Sample E does not present promising characteristics since none of the constituents present a representativity above 20% (leading to variations of results depending on the sample) and only the floating flexible black plastic, the floating rubber, the floating flexible transparent plastic and the floating rigid blue plastic melted at a temperature of approximately 180 °C, representing about 16% of the sample constitution. Their constituents and their melting points can be seen in Figure A.7.1 to Figure A.7.12;
- In sample F, only the rigid transparent plastic and the flexible transparent plastic melted at a temperature of approximately 150 °C. Silicone melted at a temperature of approximately 100 °C. Corresponding to about 17% of the sample. The results of this sample did not show promising characteristics for the following tests. Their constituents and their melting points can be seen in Figure A.8.1 to Figure A.8.9;

- Sample G started to melt at a temperature of 160 °C and presents promising characteristics for the following tests because it is homogeneous and because of its melting temperature. However, the fact that it is the only sample with commercial value may lead to other samples being taken into consideration. Their constituents and their melting points can be seen in Figure A.9.1;
- The sample H did not melt when subjected to a temperature of 200 °C. It is, however, a sample that raises some curiosity since it presents physical characteristics very different from the others. Their constituents and their melting points can be seen in Figure A.10.1;
- The sample I started to show signs of melting at around 180 °C, but did not show any promising characteristics for the following tests. Their constituents and their melting points can be seen in Figure A.11.1;
- None of the constituents of sample J melted at a temperature of around 150 °C, which means that it is not a sample with promising characteristics. Their constituents and their melting points can be seen in Figure A.12.1 to Figure A.12.6.

After reviewing the results of the melting temperatures of the 10 samples tested, and considering the objective of plastic incorporation by wet method, to modify the bitumen and guarantee a homogeneous mixture without being necessary to heat bitumen at higher temperatures to melt the plastic, the following have been selected:

- Sample B, despite being a heterogenous sample, because a large part of its constitution started to melt at a temperature close to 120 °C;
- Sample D to confirm whether its characteristics as a thermoset plastic would be maintained when in contact with bitumen;
- Sample G because it was homogeneous and started to melt near 160 °C;
- Sample H due to the curiosity to understand how a powdered plastic would behave with bitumen.

4.3 Incorporation of plastics with bitumen

Of the 4 samples tested, sample B was the easiest to partially mix with the bitumen. A well-modified and highly viscous bitumen was obtained. There was no difficulty in mixing the plastic with the bitumen, even though the latter was in a saturated state.

The result of sample D confirmed the suspicions of this being a thermoset plastic as there was no involvement of the plastic with the bitumen. This sample only has potential if the plastic is going to be incorporated via the dry method.

The plastic in sample G became partially involved with the bitumen. A modified bitumen was obtained but with less flexibility and viscosity than the modified bitumen of sample B.

The polyurethane mixture of sample H with the bitumen became extremely saturated, to the point where it was difficult to stir it. The modified bitumen did not show flexibility and viscosity characteristics as samples B and G. With the results it can be concluded that this sample does not show favourable characteristics for mixing with bitumen.

After the results are obtained, the choice of the sample to proceed with the tests would pass between sample B and G. The only advantage of sample G over sample B is its homogeneity. On the other hand, sample B showed much better results in the melting temperature test and a more flexible and viscous modified bitumen.

The environmental aspect should also be taken into account, since sample G is the only one that has commercial value, unlike sample B which is only fit for landfill or incineration.

That said, the sample that will be studied and developed in the following tests will be sample B.

4.4 Softening temperature by ring and ball test

Before starting the tests, it was already expected that the results would not be what was anticipated, because it was not possible to obtain homogeneous mixtures when incorporating the plastic with the bitumen.

Figure 4.1 shows a comparison of the results obtained between virgin bitumen and bitumen with the two sizes of plastic introduced into it. With the increase in plastic, it was expected that the bitumen would be modified, becoming more elastic and consequently increasing the softening temperature. Although there are some results with a softening temperature higher than the reference temperature, which was not in accordance with what was expected presenting some incoherence. The incorporation of 1% and 2% plastic should have resulted in a higher softening temperature than virgin bitumen, and the incorporation of 6% should have resulted in the highest temperature.

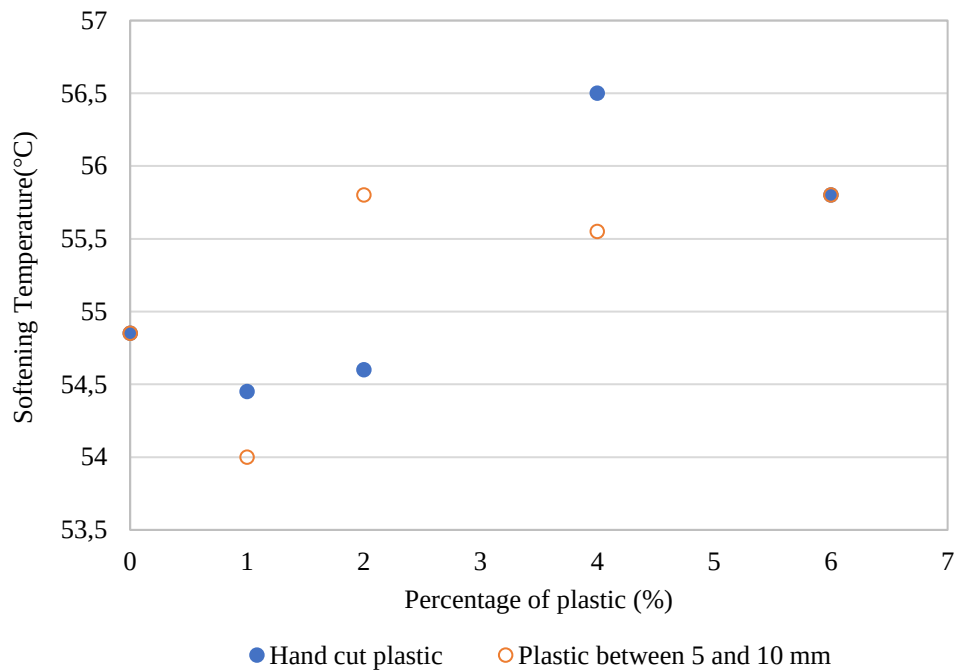


Figure 4.1 - Softening temperature - Comparison between hand-cut plastic and plastic between 5 and 10 mm

4.5 Penetration test

As with the ring and ball test, it was already expected that the results would not be as desired due to the samples not being homogeneous. A decrease in penetration was expected as the plastic would improve the characteristics of the bitumen. This decrease was observed with an increase in the percentage of plastic, however, the results within each sample were different, leading to this test being considered inconclusive. Figure 4.2 shows a comparison between hand-cut plastic and plastic between 5 and 10mm.

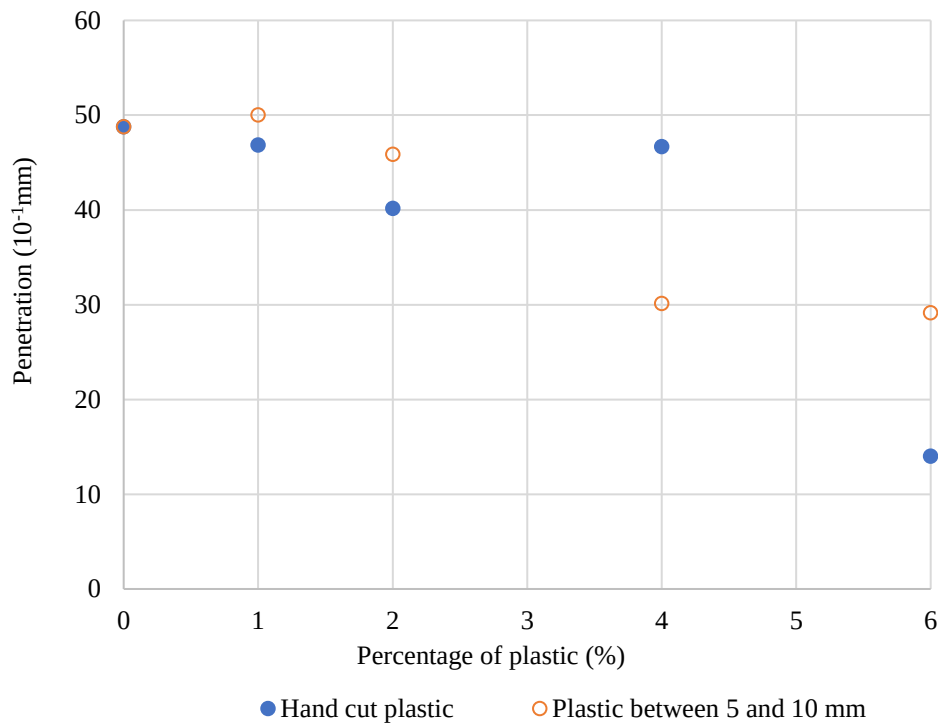


Figure 4.2 - Penetration test – Comparison between hand-cut plastic and plastic between 5 and 10 mm

4.6 Incorporation of plastics by dry method

During the placement of the plastic with the aggregate at 200 °C, there was difficulty in mixing before placing the bitumen because the plastic when coming into contact with the heated aggregate started to melt and stick to the mixer helix. Before adding the bitumen it was necessary to remove the plastic attached to the mixer helix.

After adding the bitumen, the whole formed a ball while being mixed, as shown in Figure 4.3 I.

After mixing and passing into the Marshall mould, 75 blows were given on each side and it was observed that the specimen formed a deformation, it is believed that this deformation is due to a certain part of the plastic having behaved like bitumen, so it is necessary to decrease the bitumen content. Figure 4.3 II shows this behaviour.

It was also noted that the large amount of plastic, totalling 10%, contributed to the specimens exceeding the dimensions suggested for the Marshall tests, which is 63.8 mm in height. The mass of the sample was therefore reduced from 1200 g to 1080 g to obtain specimens with the desired dimensions.

Therefore, further tests will be carried out to find the optimum bitumen content for 1080 g of mixture mass.



I)



II)

Figure 4.3 - I) A ball formed in the mixture when bitumen was added; II) Specimen deformation

4.7 Optimum bitumen content

The specimens in question were acquired following the specifications necessary for the Marshall test. As observed in Figure 4.4 the base of these specimens varies - some have a smooth base coated with bitumen, while others have a base where the aggregates are partially coated with bitumen. This is due to the difficulty in mixing the materials, caused by the formation of a ball during the mixing process, as illustrated in Figure 4.3 Label I. This results in parts of the aggregate becoming isolated at the bottom of the mixing pan, preventing them from being properly mixed.

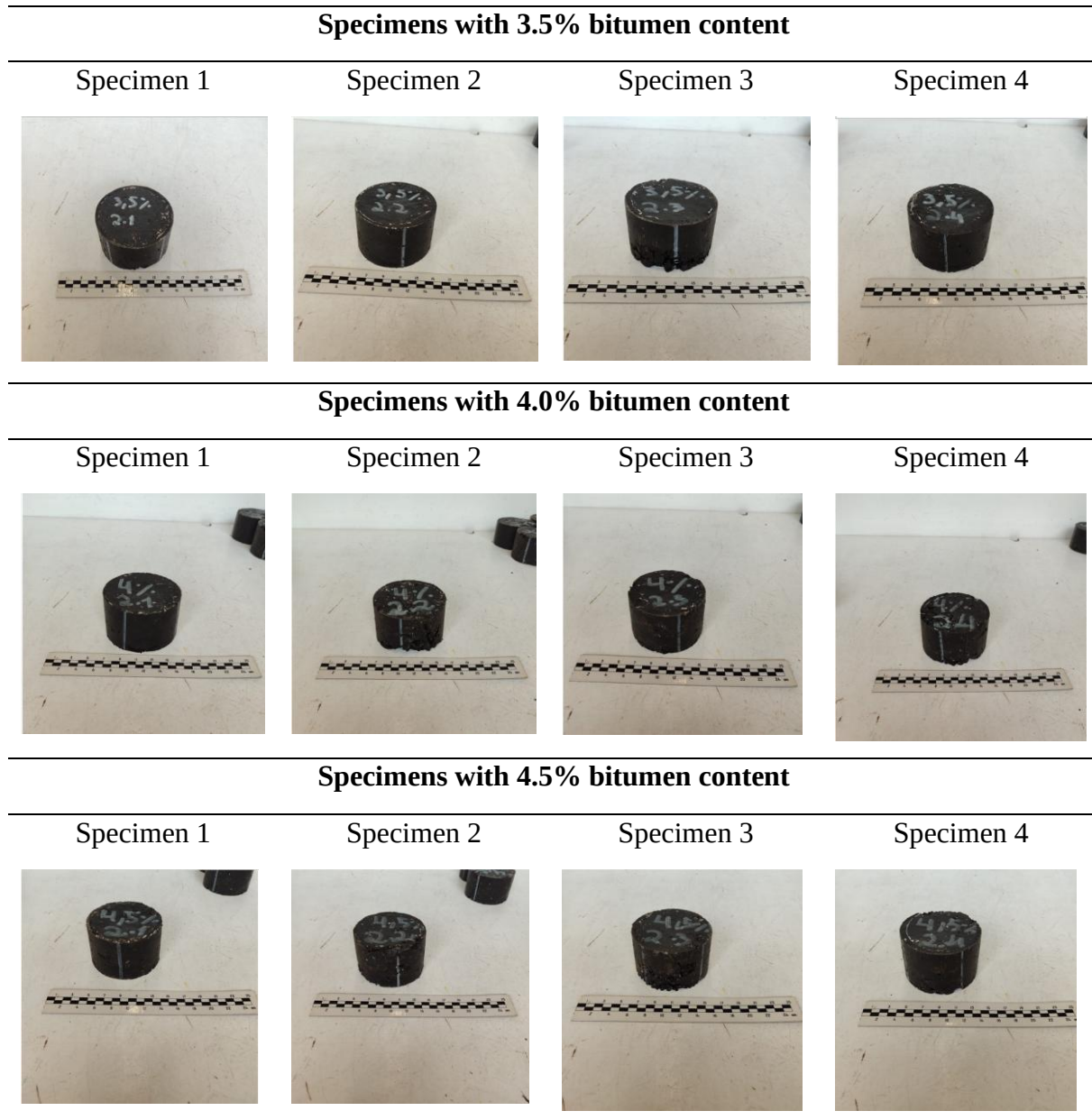


Figure 4.4 - Marshall specimens with 1080 g

4.7.1 Decision on the optimum bitumen content

To choose the optimum bitumen content to proceed with the following tests, it was evaluated the porosity, Marshall stability, VMA and deformation concerning the three bitumen contents tested, obtaining Figure 4.5: I); II); III) and IV) respectively.

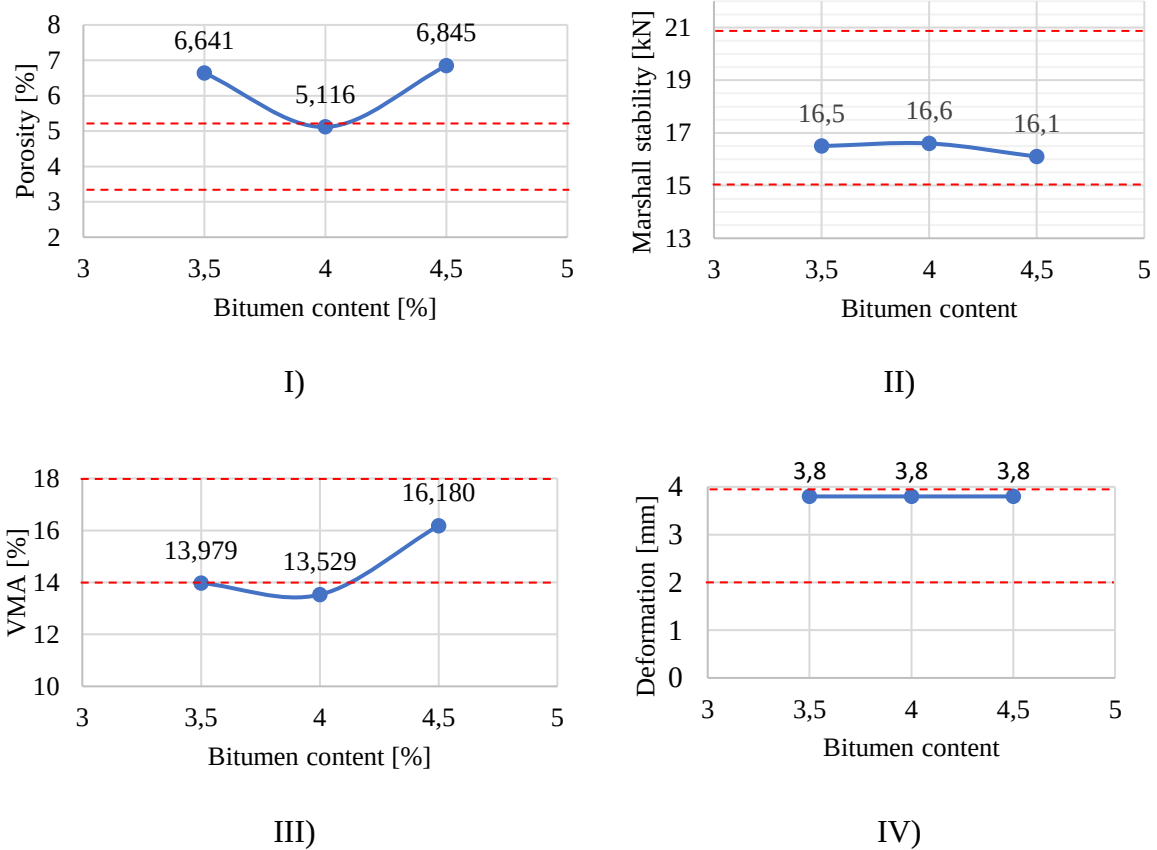


Figure 4.5- I) Porosity [%]; II) Marshall Stability; III) VMA [%]; IV) Deformation [mm]

The charts with red dotted lines serve to indicate the desired range values. Based on Figure 4.5 I, the preferred range for porosity is between 3 and 5%, with the bitumen content closest to this range being 4%. Thus, a bitumen content of 4% was chosen. When it comes to Marshall stability values, Figure 4.5 II demonstrates that all values fall within the desired range for every bitumen content. Therefore, a 4% bitumen content for this factor was chosen. Regarding VMA, Figure 4.5 III shows that only the 4.5% bitumen content has a value within the desired range. Meanwhile, Figure 4.5 IV indicates that there are no variations in deformation across different bitumen contents. As such, the type of bitumen content is not relevant for this aspect. However, according to Table A.15, the 4% bitumen content corresponds to the highest density level. To achieve an average of four bitumen contents closer to 4%, a 4.5% content was adopted.

Therefore, the OBC will be the average between 4%, 4%, 4.5% and 4.5% which will correspond to a rounded down value of 4.2%.

4.8 Water sensitivity

The groups were separated according to the standard. The first group consists of specimens 1, 2 and 4 and the second group consists of specimens 3, 5 and 6. It was decided that the first group would be the group exposed to dry conditions and the second group would be the group exposed to water. This decision was made because group 2 had a higher average bulk density than the other group. Table A.19 shows some of the important data for this study, as well as providing that the volume variation for the second group did not exceed the maximum volume variation of 2%. The type of failure that occurred in the specimens between Figure A.20.1 and Figure A.20.6 will also be mentioned, where a), b) and c) correspond to:

- a) Clear tensile break – Specimen is clearly broken along a diametrical line, except perhaps for small triangular sections close to the loading strips;
- b) Deformation – Specimens without a clearly visible tensile break line;
- c) Combination – Specimens with a limited tensile break line and larger deformed areas close to the loading strips;

Figure 4.6 illustrates the determination of the water sensitivity assessed by the indirect tensile strength (ITS_R).

Figure 4.6 I), the results for the indirect dry resistance (ITS_D) and indirect wet resistance (ITS_W) of bituminous mixtures with plastic and the reference mixture are presented. Under dry conditions, the mixture with plastic exhibited a value of 1.8 MPa, while the reference mixture showed 2.4 MPa for ITS_D . Under wet conditions, the mixture with plastic reached 1.82 MPa and the reference mixture obtained 2.3 MPa for ITS_W .

Figure 4.6 II) illustrates that the mixture with plastic achieved an ITS_R of approximately 101%, surpassing the 100% mark. In contrast, the reference mixture achieved an ITS_R of approximately 95%, indicating a 5% reduction in tensile strength when exposed to water compared to the dry condition.

The results clearly demonstrate the advantage of incorporating plastic in bituminous mixtures in maintaining tensile strength in wet conditions. The high ITS_R value indicates superior durability and resilience for the plastic mixture, even when subjected to extreme conditions.

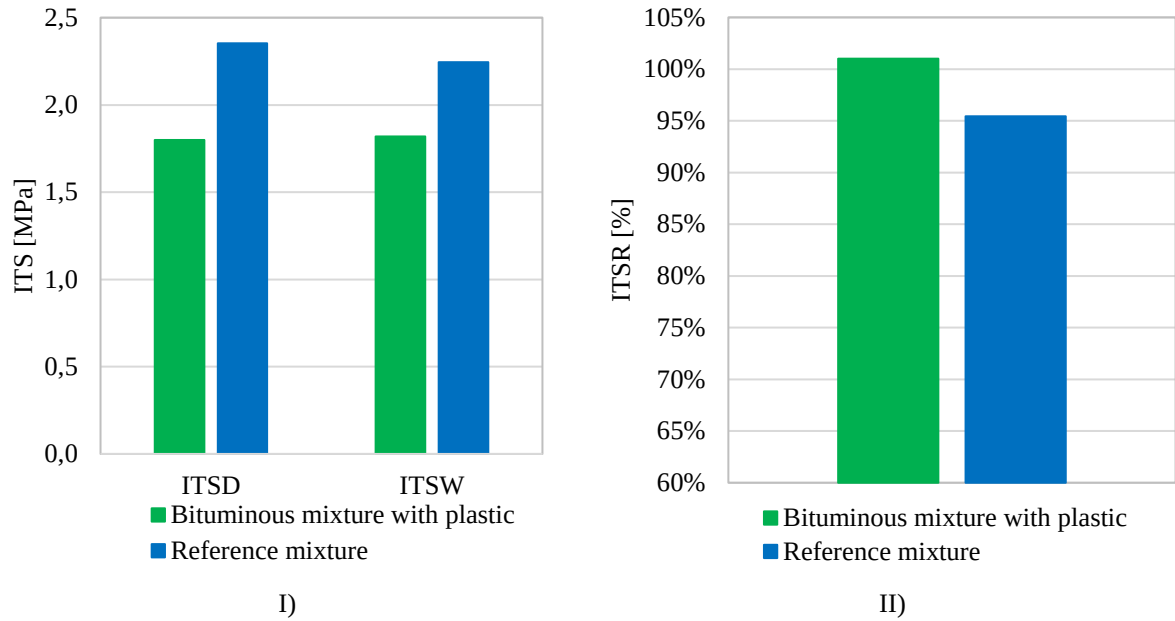


Figure 4.6 - I) Indirect dry resistance and Indirect wet resistance [MPa]; II) Indirect tensile strength [%]

4.9 Wheel tracking

The test was based on three main parameters: the mean rut depth at 10.000 cycles [RD_{AIR}], the wheel tracking slope in the air [WTS_{AIR}], which relates the rut depth to the number of loadings cycles, and the mean proportional rut depth [RPD_{AIR}], which is the depth of the rut concerning the thickness of the bitumen layer. The data for the two mixtures can be found in Table A.21.

Figure 4.7 illustrates the relation between rut depth and the number of cycles for the bituminous mixture with plastic and the reference mixture.

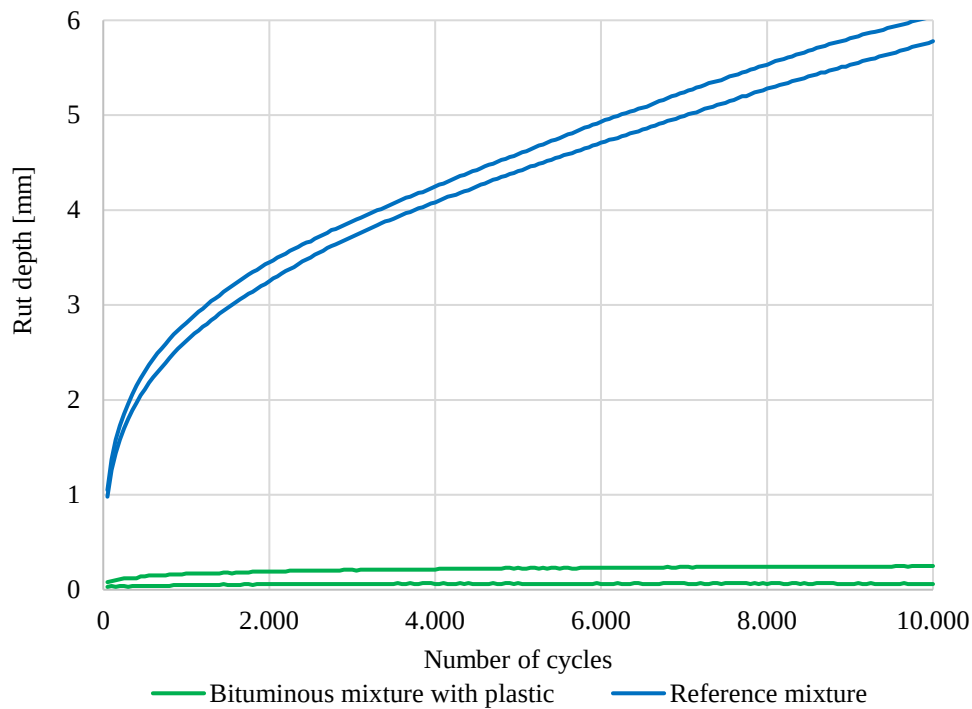


Figure 4.7- Permanent deformation

According to Figure 4.7, the rut depth in the bituminous mixture with plastic is minimal, resulting in an RD_{AIR} of 0.2 mm, unlike the reference mixture which has an RD_{AIR} of 5.9 mm. These results indicate that, in the case of surface course, the BM incorporated with plastic is highly resistant to permanent deformation, showing very significant improvements in pavement resistance.

4.10 Macrotexture

The results of this test were inconclusive because there was not enough surface area to spread the glass spheres, as can be seen in Figure 4.8 I. This was since the surface of the slab was extremely smooth and without irregularities, as can be seen in Figure 4.8 II, demonstrating an inability to support the spheres throughout their spreading. This reveals a surface with no capacity to guarantee safety conditions, specifically skid resistance.



Figure 4.8- I) Insufficient surface to spread the glass spheres; II) Smoothness and lack of irregularities in the slab

To enhance the surface, another slab was produced with the compaction phase vibration turned off, as it was suspected that the vibration might be causing bitumen exudation. However, there was no discernible difference in the surface of the new slab.

4.11 Microtexture

Table 4.1 shows the readings recorded for the two slabs in the pendulum test, as well as the initial temperatures (T_i) and final temperatures (T_f) of the rubber.

Table 4.1 - Measurements taken during the pendulum test

Parameters	Slab 1					Slab 2				
T_i (°C)	18.4					15.8				
T_f (°C)	17.3					16.2				
PTV	37.0	37.0	37.0	37.0	37.0	40.0	40.0	40.0	40.0	40.0
Average	37.0					40.0				

The pendulum test values fall significantly below the minimum requirement set by Portuguese road regulations, which is 60 PTV (Estradas de Portugal, 2014). These results, in conjunction with those of the macrotexture test, indicate that the road surface is unsuitable for a wearing course and therefore does not ensure safety conditions, particularly concerning skid resistance.

4.12 Stiffness modulus

As mentioned in Chapter 3.14, the tests were carried out at temperatures of 10 °C, 20 °C and 30 °C. The data in the graphs provide insights into the stiffness, phase angle, and viscoelastic behaviour of these mixtures in response to temperature and frequency cycles.

The various results obtained in this test can be found below, where Figure 4.9 I to IV correspond to stiffness, phase angle, E_1 and E_2 .

- In Figure 4.9 I, it is observed that the mixtures with plastic have lower stiffness, especially at 10 °C and 20 °C, but they show greater stability with smaller variations between temperatures. On the other hand, the reference mixtures demonstrate larger increases as the frequency rises. Notably, at 30 °C, the plastic mixture exhibits slightly higher stiffness than the reference mixture. Overall, mixtures with plastic have lower stiffness than the reference mixtures but display greater stability in terms of stiffness variation with temperature;
- In Figure 4.9 II, the phase angles (ϕ) of the reference and plastic mixtures at different temperatures and frequencies are illustrated. The reference mixtures show larger ϕ , particularly at 30 °C, decreasing with frequency, while mixtures with plastic exhibit smaller and more consistent ϕ at all temperatures. Mixtures with plastic display lower ϕ and are less susceptible to frequency variations, suggesting a reduced tendency for viscous deformation, especially at lower temperatures;
- Figure 4.9 III illustrates the real component (E_1) values of the reference and plastic mixtures at different temperatures and frequencies. The reference mixtures demonstrate higher E_1 values at 10 °C and 20 °C, while the plastic mixtures show lower E_1 values and greater stability as frequency increases. However, at 30 °C, the plastic mixture displays higher E_1 values compared to the reference mixture. Mixtures incorporating plastic generally exhibit lower E_1 values, indicating increased flexibility compared to the reference mixtures;
- Figure 4.9 IV, the imaginary component (E_2) values of the reference and plastic mixtures are compared. The reference mixture exhibits higher E_2 values across all temperatures. The plastic mixtures demonstrate lower E_2 values, indicating reduced rigidity compared to the reference mixtures, but they display enhanced stability in response to frequency variation;

Overall, the plastic mixtures show lower stiffness, less susceptibility to frequency variations, and increased flexibility compared to the reference mixtures, indicating their potential for applications in pavements subject to variable traffic and climate conditions, ensuring consistent performance.

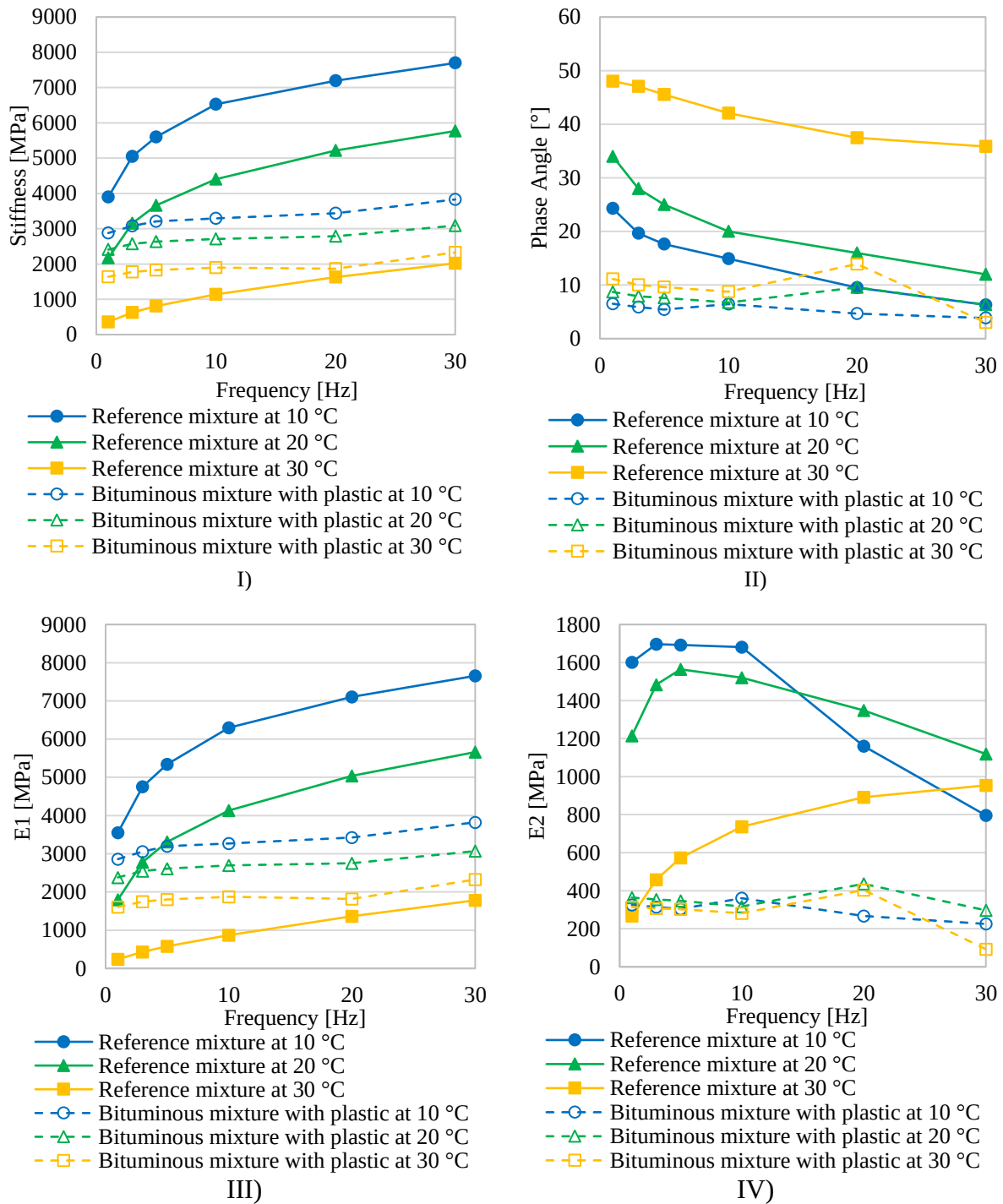


Figure 4.9 - I) Stiffness and Frequency; II) Phase Angle and Frequency; III) E₁ and Frequency; IV) E₂ and Frequency

4.13 Fatigue

The fatigue tests were conducted to provide a clearer understanding of the behaviour of the bituminous mixture under investigation. However, as this study focuses on a surface course rather than a binder or base course, fatigue is of lesser significance. Instead, stiffness, water sensitivity and permanent deformation are the more critical factors for the course being analysed.

Figure 4.10 shows the relation between the extensions and the number of cycles to failure for the studied BM and the reference mixture.

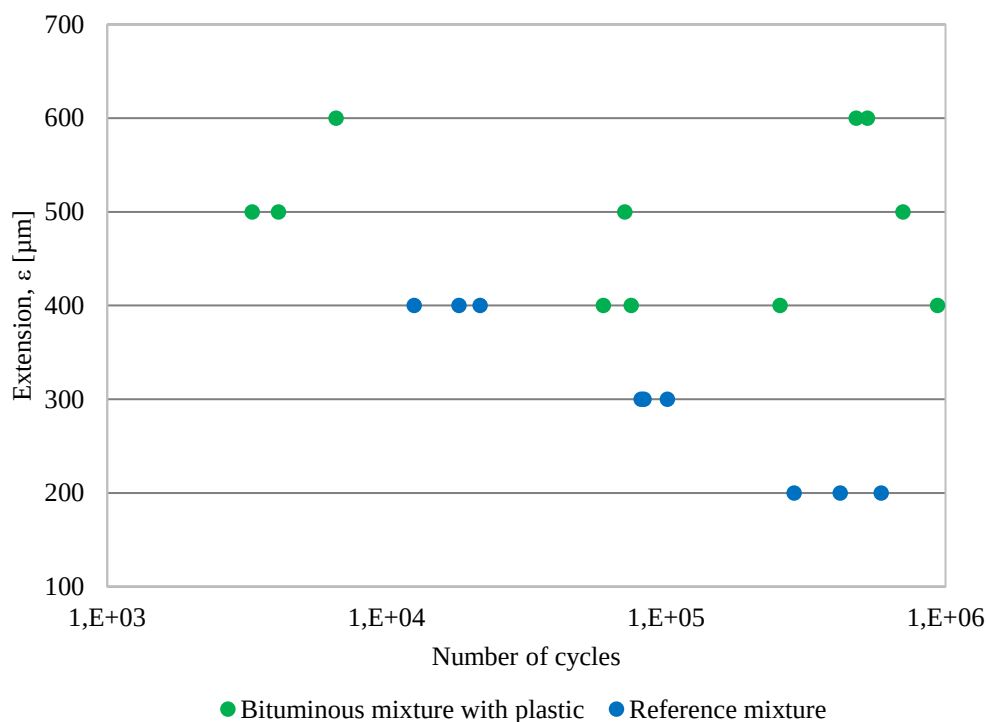


Figure 4.10 - Fatigue results

The test to determine the fatigue resistance of BM incorporated with plastic revealed a wide variation in the number of cycles to failure, even at the same extension. Specifically, for an extension of 400 μm , the cycles to failure ranged from 59 600 to 936 000. In contrast, the reference mixture at the same extension showed significantly lower cycles to failure values and a much smaller variation. This variability in the BM incorporated with plastic may be attributed to an inefficient distribution of the plastic, leading to certain beams having different amounts of plastic from each other. However, it should be emphasized that all the beams with extensions in common with the reference mixture required more cycles to reach failure, which indicates

that the BM incorporated with plastic have a higher fatigue resistance, significantly influencing the durability of the mixture after repeated loading.

The fatigue resistance results can be consulted in Table A.22.

Despite not having reliable data to obtain a fatigue law, it was decided to present it with a low degree of confidence to be able to further analyse the subject. The fictitious coefficients of the strain fatigue law for the different mixtures are presented in Table 4.2.

Table 4.2 - Fictitious coefficients of the strain fatigue law

Mixture	k_1	k_2
Bituminous mixture with plastic	551.17	-0.011
Reference mixture	3151.3	-0.211

Figure 4.11 presents a comparison of the failure values for both mixtures. For ϵ_4 , the BM incorporated with plastic exhibited an extension of approximately 498 μm , whereas the reference mixture only withstood 451 μm . This difference became more apparent at ϵ_5 and ϵ_6 , with the BM incorporated with plastic enduring 486 μm and 473 μm respectively, compared to the reference mixture, which sustained only 278 μm and 171 μm at the same cycle counts. These results indicate the notable advantage of BM incorporated with plastic, as it maintains significantly high fatigue resistance even after a large number of cycles.

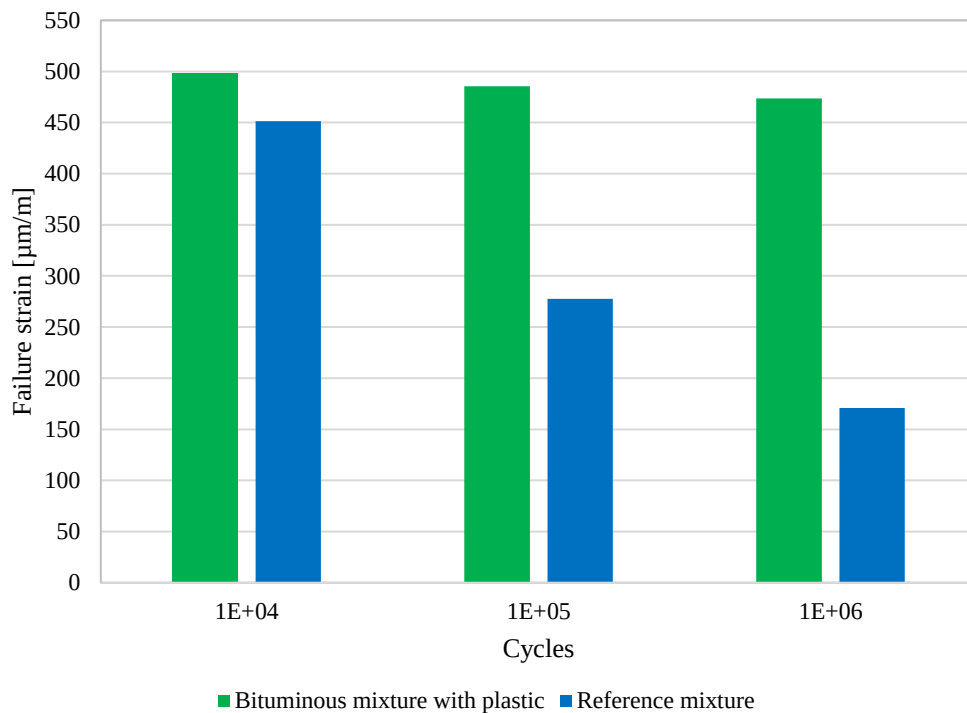


Figure 4.11 - Strain needed for fatigue failure

4.14 Bitumen recovery

The objective of the laboratory procedure was to evaluate the impact of incorporating plastic on the bitumen, using penetration and ring and ball tests. However, these tests were not conducted because even after 20 hours of the bitumen recovery, the bitumen remained in an excessively liquid state. The condition of the bitumen is illustrated in Figure 4.12.

Additionally, it was observed that contrary to expectations, the bituminous mixture still contained fractions of bitumen after 1 hour in toluene, as depicted in Figure 4.12 II. It is important to note that crushing the BM using a press was extremely challenging and required the manual use of a hammer. The condition of the BM after pressing can be seen in Figure 4.12 III.

It is possible to mention that from the tests carried out, which include the standardised procedure, it is not possible to recover the bitumen in this bituminous mixture.

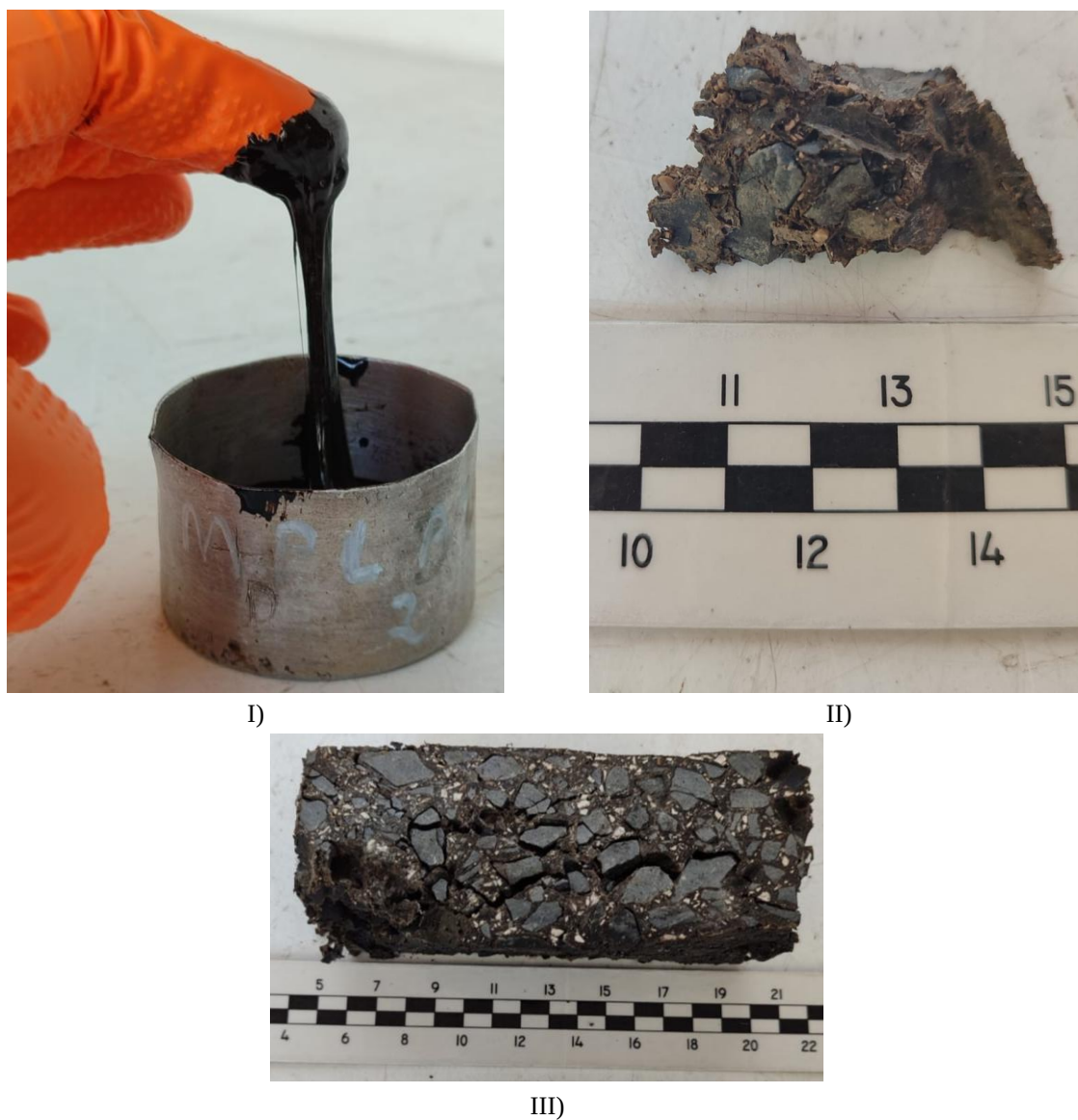


Figure 4.12 - I) Bitumen after 20 hours; II) Bitumen present after 1 hour in toluene; III) Bituminous mixture after pressing

5 Environmental and economic analysis

As plastics are derived from fossil fuels, greenhouse gases are released at all stages of their life cycle: extraction and transport of fossil fuels, production of polymers and the conversion of these polymers into intermediate products, the end-of-life phase, when waste is sent for recycling, incineration or landfill, and their ongoing impact due to their environmental dispersion (Hamilton et al., 2019; European Topic Centre Waste and Materials in a Green Economy, 2021). The total GHG emissions caused by the plastics value chain in the European Union in 2018 is estimated at 208 million tonnes of carbon dioxide. Of these emissions, 63% are caused by their production, 22% by the conversion of polymers into products and 15% by the treatment of end-of-life waste, particularly through incineration (European Topic Centre Waste and Materials in a Green Economy, 2021).

Plastic production has a significant impact on GHG emissions, which are expected to reach 1,34 gigatonnes of CO₂ per year by 2030 (Hamilton et al., 2019). Considering the variability between types of plastic, the production of 1kg of virgin plastic of fossil origin results in at least 2,9 kg of GHGs (European Topic Centre Waste and Materials in a Green Economy, 2021).

The disposal of plastics in landfill sites generates considerable CO₂ emissions, estimated at 253 g/kg (Eriksson & Finnveden, 2009). This is due to the degradation of plastic, which emits CO₂ and methane into the atmosphere (Tonini et al., 2021). Another problem related to the end of life of plastic in landfills, more specifically in open dumps or landfills with defects, such as flaws in landfill liners, is the release of microplastics, which is considered the main source of microplastic release. It is estimated that landfills contributed to the release of around 4.1 million megatonnes of the 9.2 million megatonnes of microplastics that were lost to the environment in 2015 (Yadav et al., 2022).

When plastic is burnt, it emits GHGs, mainly CO₂. It can also emit dangerous chemicals into the environment depending on the type of plastic and how its waste is treated (Hamilton et al., 2019). The incineration of plastic, especially packaging, is responsible for a substantial amount of GHG emissions, totalling 16 million tonnes of CO₂ in 2015 for this type of product alone (Hamilton et al., 2019). CO₂ emissions can vary, reaching 4,605 g/kg, depending on the type of polymer and the incineration practices adopted (Eriksson & Finnveden, 2009).

To compare the quantity of materials and the cost of using bituminous mixtures with plastic as opposed to a reference bituminous mixture, a case study was carried out of a wearing course for a 1 km long road with two lanes of 3 m, one in each direction, and 1 m wide roadsides. Table A.23 shows the dimensions of the road and the required mass of the bituminous mixture.

The quantities of each constituent material of the bituminous mixtures, as well as the associated costs for the construction of each kilometre of road, with a cross-sectional profile, are shown in Table A.24.

The unit price of the materials does not take transport distances into account, since similar transport distances are assumed between the various materials used.

Comparing the results shown in more detail in Figure 5.1, it can be seen that the quantities of basalt aggregate and commercial filler are similar between the two mixes, causing no significant cost variation.

For the bituminous mixture with plastic, 147.7 megagrams less limestone is needed compared to the reference mixture, which translates into a cost of 2 363.3 €/km. The greatest contribution of the mixture investigated is the reduction in the amount of bitumen, which reduces the cost by approximately 15 756 €/km.

Taking into account all the constituents of the bituminous mixtures under comparison, it is possible to determine a cost reduction per kilometre of a road of around 19 838.8 €, corresponding to a percentage reduction of 26.5% per kilometre of road, highlighting the potential for incorporating plastic waste into bituminous mixtures.

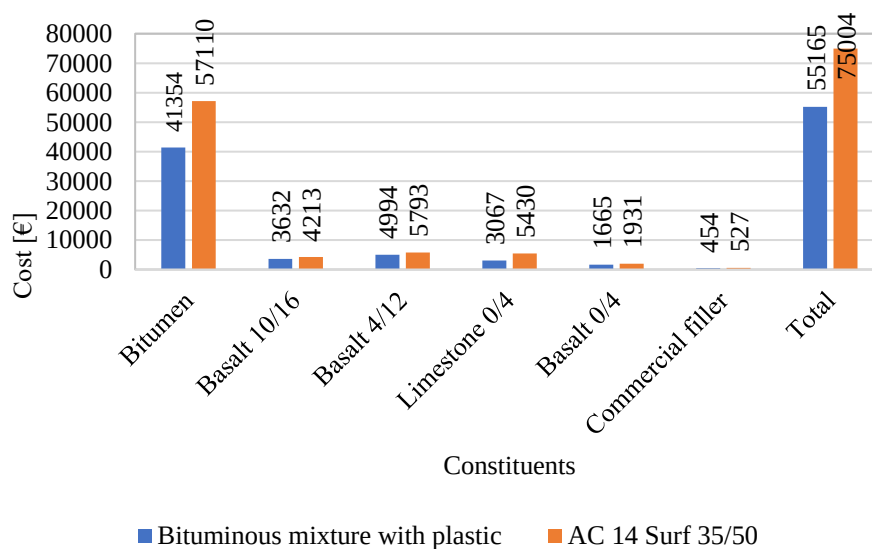


Figure 5.1 - Cost comparison of the various constituents of the mixtures

6 Final considerations

6.1 Conclusions

The present study intended to investigate non-recyclable plastic waste incorporation in the bituminous mixture, seeking to surpass the reference standards. To achieve the main goal of the study ten samples of plastic waste were selected. Through visual sorting and density tests with water, 75 samples were derived. Several initial tests were performed to assess their suitability for incorporation into bituminous mixtures. The study continued with the dry method, where a bituminous mixture with 10% plastic was formulated from Marshall's tests. Tests were then carried out on water sensitivity, wheel tracking, macro and micro-texture, fatigue and stiffness modulus to see if there was an improvement in the properties of the bituminous mixture.

Out of the ten samples tested for incorporation in bituminous mixtures, six were found to be heterogeneous, while the remaining four were homogeneous. Analysis of the samples and their melting point tests revealed that those suitable for bituminous mixtures possess lower melting temperatures, resulting in a density lower than that of water. Notably, Sample B, a heterogeneous sample, had 77% of its constituents melting at 120 °C. Incorporating this sample in bitumen resulted in a highly viscous and modified mixture, which facilitated an easier blend with the bitumen.

Attempts to incorporate the selected samples using the wet method proved inconclusive due to inconsistent results in penetration and softening temperature by ring and ball tests. This was attributed to the failure to achieve a homogeneous mixture between the bitumen and plastic at temperatures up to 175 °C.

Using the dry method, to incorporating 10% plastic relative to the total weight of aggregate, it was determined that the OBC is 4.2%. This is lower than that of reference mixtures, as the melted plastic tends to acquire binding properties similar to bitumen. The resulting mixture exhibited excellent water sensitivity and showed no degradation upon exposure to water, indicating that it would maintain its durability under adverse weather conditions if used as a surface course.

The wheel tracking test results demonstrated high resistance to permanent deformation and pavement strength, with an RDAIR of only 0.2mm for the tested slabs. Regarding the texture of the BM, the results were concerning. The surface characteristics of the slab revealed an extremely smooth surface, compromising safety conditions, particularly in terms of skid

resistance. These poor conditions were not due to bitumen exudation during the compaction phase, as the BM were compacted with and without vibration. Consequently, this BM is currently not suitable for the surface course and may be more appropriate for the binder course.

Furthermore, the stiffness of bituminous mixtures varies with temperature. At 10 °C, these mixtures exhibit high stiffness. However, at 20 °C and 30 °C, the stiffness decreases, suggesting that the plastic provides greater flexibility at higher temperatures. These adjustments enable BM to offer better performance in cold climates by providing greater rigidity and in hot climates by offering greater flexibility, contributing to the durability and resistance of pavements in various environmental conditions.

The BM incorporated with plastic exhibits significant fatigue resistance compared to the reference mixture. All the samples of BM with plastic that had the same extensions as the reference mixture required more cycles to reach failure, indicating a superior fatigue resistance. Additionally, at different cycle levels (ϵ_4 , ϵ_5 and ϵ_6) the studied mixture endured greater extensions before failure compared to the reference mixture, showcasing better resistance even after a substantial number of cycles. These results emphasize the advantage of plastic incorporation in bituminous mixtures, which contributes to enhancing the durability of the mixture under repetitive loads.

In the context of bitumen recovery, the test showed that the obtained bitumen sample was too liquid after 20 hours of cooling to proceed with penetration and ring and ball tests. Additionally, 1 hour in toluene was insufficient to dissolve all the bitumen.

Economically, using this BM is significantly more cost-effective compared to the AC 14 Surf 35/50 reference mixture, with a 26.5% reduction in cost per kilometre of the road due to the reduced need for raw materials such as limestone and bitumen.

In summary, the incorporation of plastics in bituminous mixtures holds significant potential for transforming waste management and road pavement construction. Despite challenges related to the mixture homogeneity and pavement surface characteristics, the benefits in terms of durability, water resistance, and cost savings are promising. Continued development of methodologies to overcome current limitations is crucial to fully harness these opportunities. Embracing sustainable and innovative practices will not only contribute to environmental preservation but also promote more efficient and durable road infrastructure for future generations.

6.2 Future works

A significant proportion of the plastics incorporated and studied in bituminous mixtures are essentially plastics processed specifically for this purpose, namely plastic pellets. The incorporation of non-recyclable plastics offers similar benefits as processed plastics, along with an environmental contribution, but it is still in a relatively embryonic stage. This will be an ongoing research topic requiring further improvements. Some recommendations for the enhanced incorporation of non-recyclable plastics will be discussed below:

Beginning with the plastic treatment phase, the plastics need to be separated more rigorously, facilitating investigation without the need for multiple separations within each sample. In the case of one heterogeneous sample containing many different constituents, where some plastics had potential for incorporation, separating them might pose significant constraints, thus preventing their incorporation.

It would be worthwhile to investigate homogeneous samples such as Sample D in greater detail, as it exhibits promising characteristics for replacing fine portions of aggregate using the dry method. Other types of homogeneous plastic samples with low melting points may also be of interest to examine, to determine if their behaviour is consistent with the results obtained from the sample used in this study.

Although the selected sample was not incorporated using the wet method, it would be beneficial to investigate and analyse the results of the BM formed using this method. Even though a homogeneous mixture between bitumen and plastic was not achieved, it is worth analysing whether the bitumen was modified and if it exhibited improved characteristics compared to the reference bitumen.

Further investigation into the formulation and mixing of the BM is recommended. This includes reviewing whether altering any aggregate or adjusting the duration or temperature of the mixture would enhance the surface conditions of the pavement.

To gain a better understanding of bitumen behaviour, it is crucial to conduct a chemical analysis of the recovered bitumen. Further recovery tests should be carried out with modifications to improve the quality of the recovered bitumen, such as attempting to dissolve the bitumen that remained in the aggregate. This would also allow to examine whether the plastic remains attached or detached to the aggregate and help develop a strategy for multi-recycling it at the end of the life of these bituminous mixtures.

Finally, a highly recommended future direction is to investigate the chosen sample by formulating a BM with a lower percentage of plastic. Two scenarios should be tested: using

half and a quarter of the amount studied. This research is necessary because the density of the plastic makes the 10% incorporation rate extremely high compared to the aggregate density. It would be valuable to see if reducing the amount of plastic would improve the surface characteristics of the BM while maintaining its resistance capacity.

Moreover, it is crucial to study the end-of-life phase of this mixture, particularly if it is used in a surface course. This includes investigating whether microplastics would be released into the environment due to polishing from vehicles and weathering.

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Annexes

Annexe 1: Images of plastics samples collected and analysed



Figure A.1.1 - Sample A



Figure A.1.2 - Sample B



Figure A.1.3 - Sample C

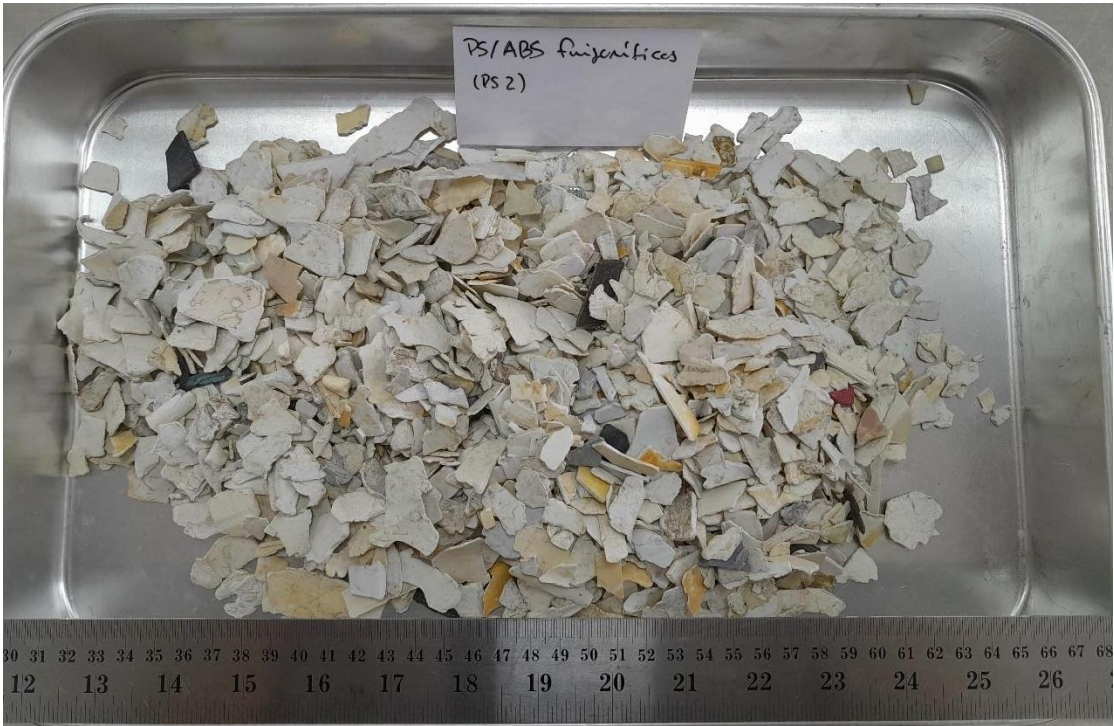


Figure A.1.4 - Sample D



Figure A.1.5 - Sample E



Figure A.1.6 - Sample F



Figure A.1.7 - Sample G

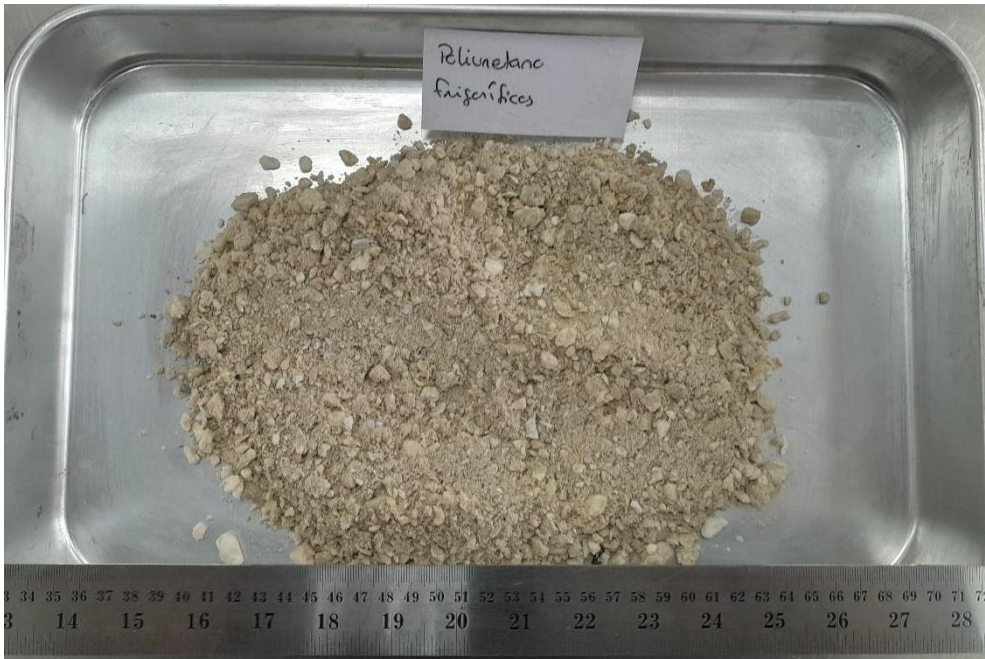


Figure A.1.8 - Sample H



Figure A.1.9 - Sample I



Figure A.1.10 - Sample J

Annexe 2: Plastic samples constitution

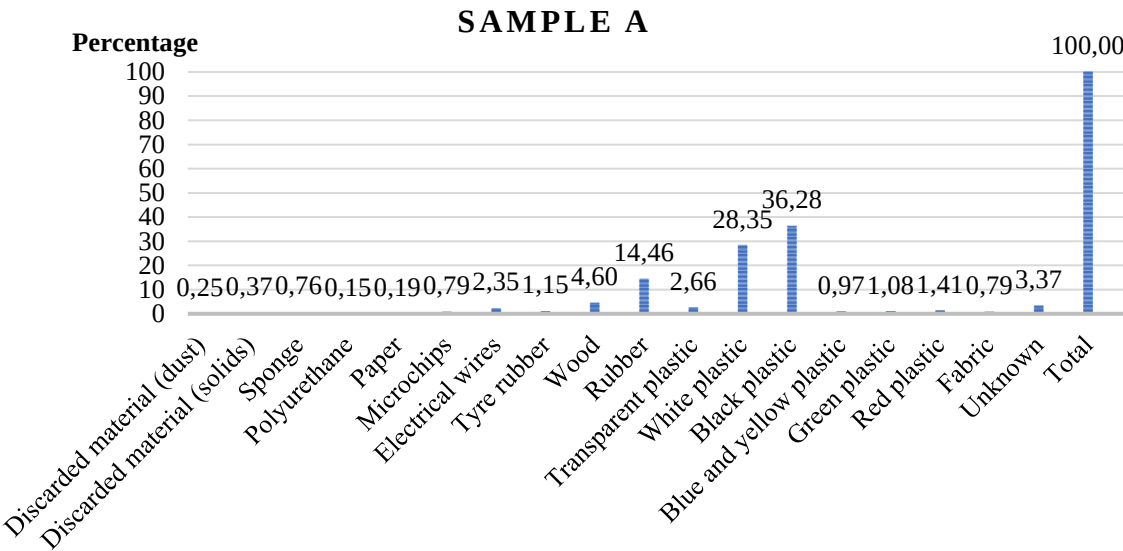


Figure A.2.1 - Constitution of sample A

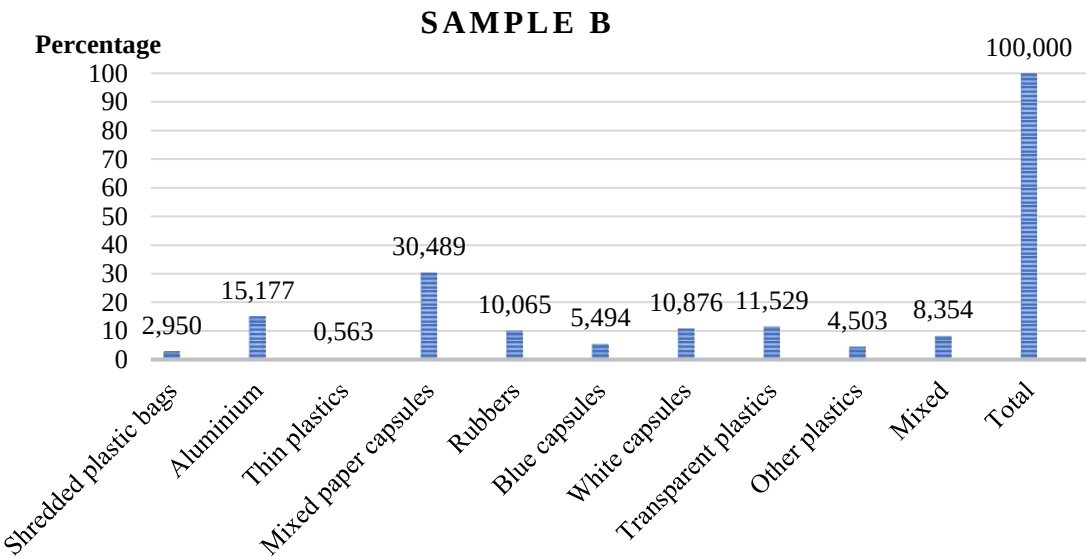


Figure A.2.2 - Constitution of sample B

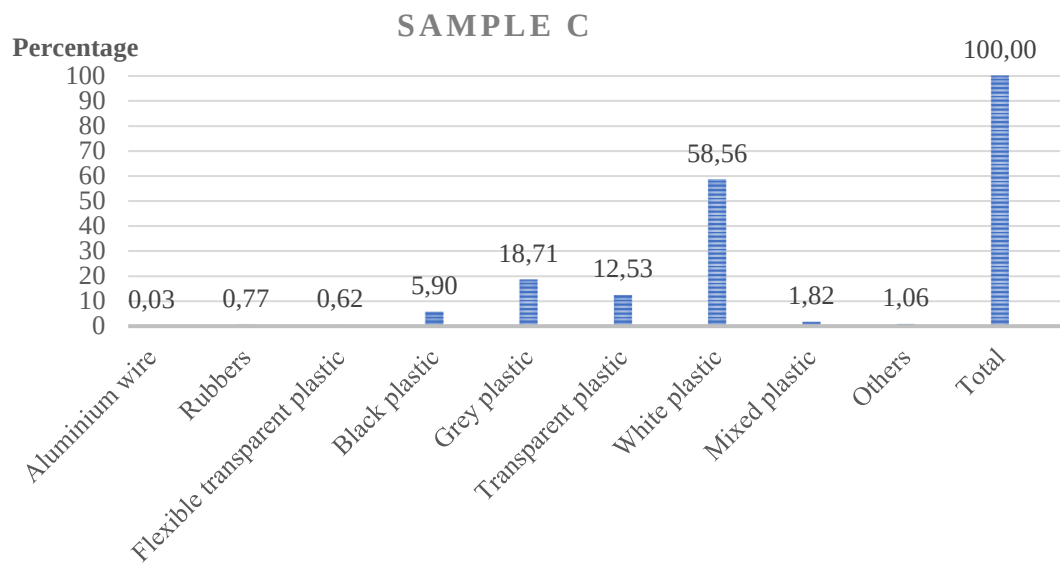


Figure A.2.3-Constitution of sample C

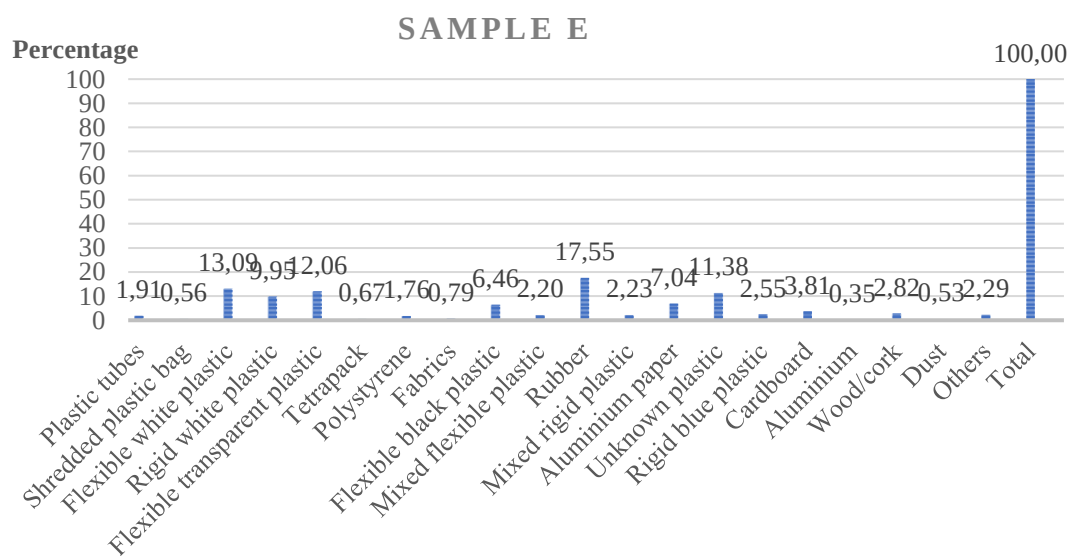


Figure A.2.4 - Constitution of sample E

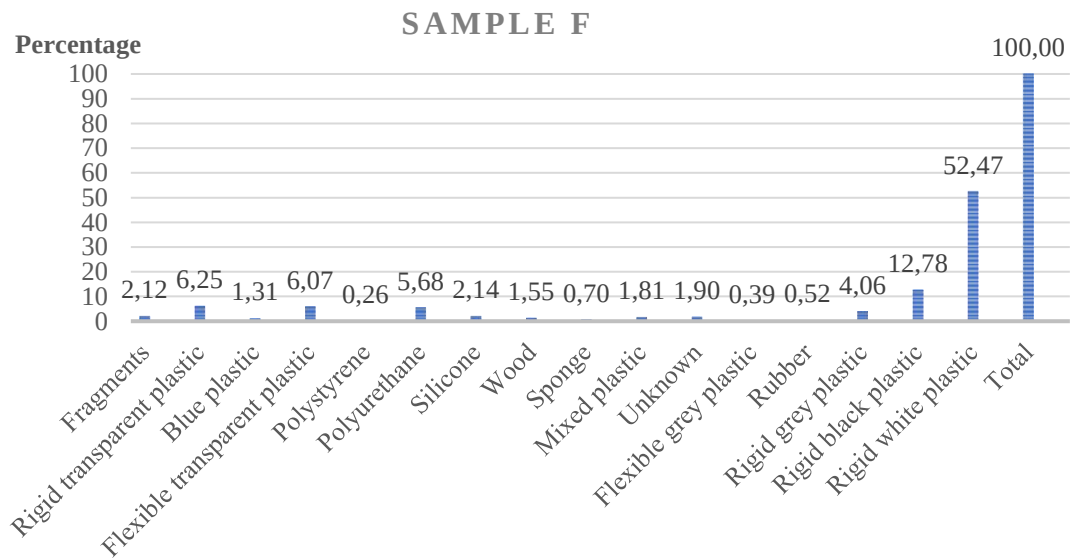


Figure A.2.5 - Constitution of sample F

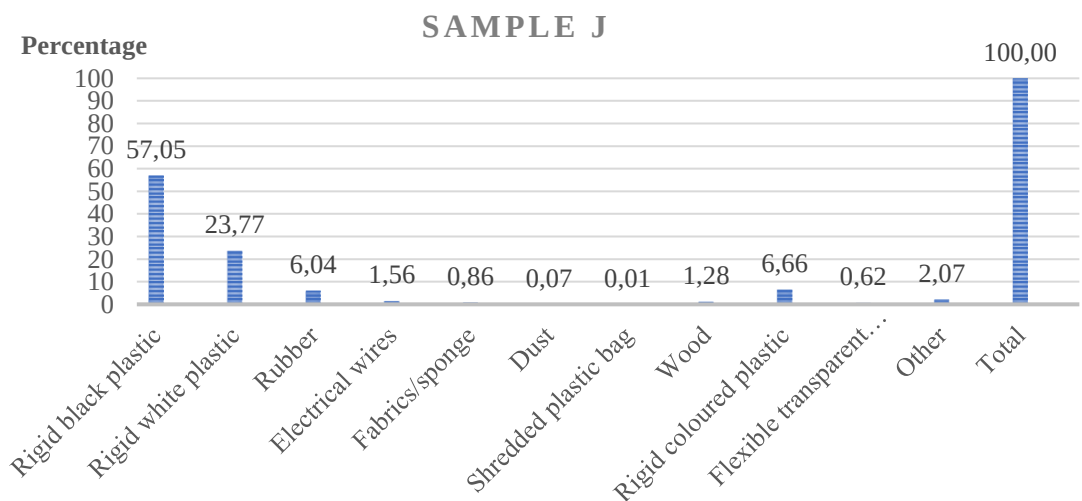


Figure A.2.6 - Constitution of sample J

Annexe 3: Melting point of sample A

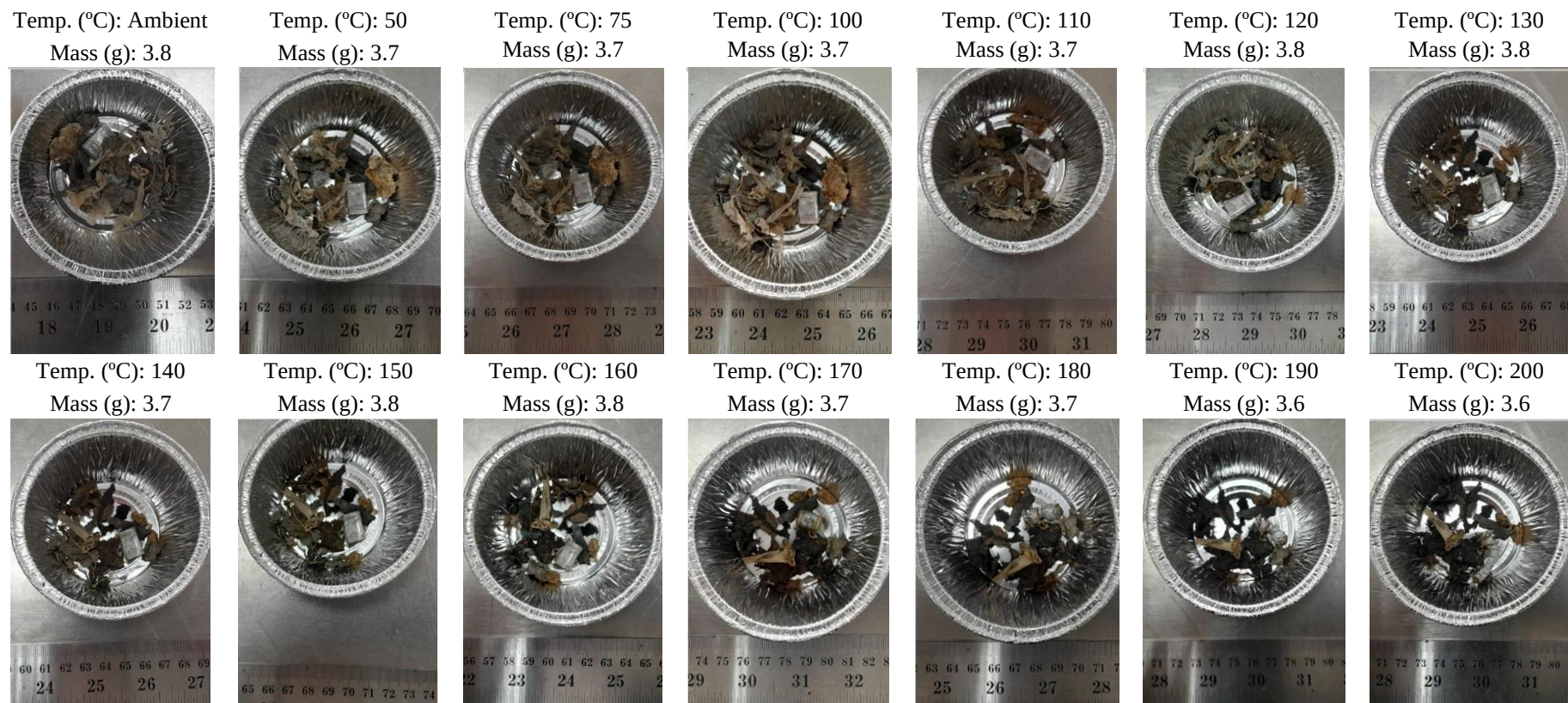


Figure A.3.1 - Sample A – Discarded materials – Floating solids

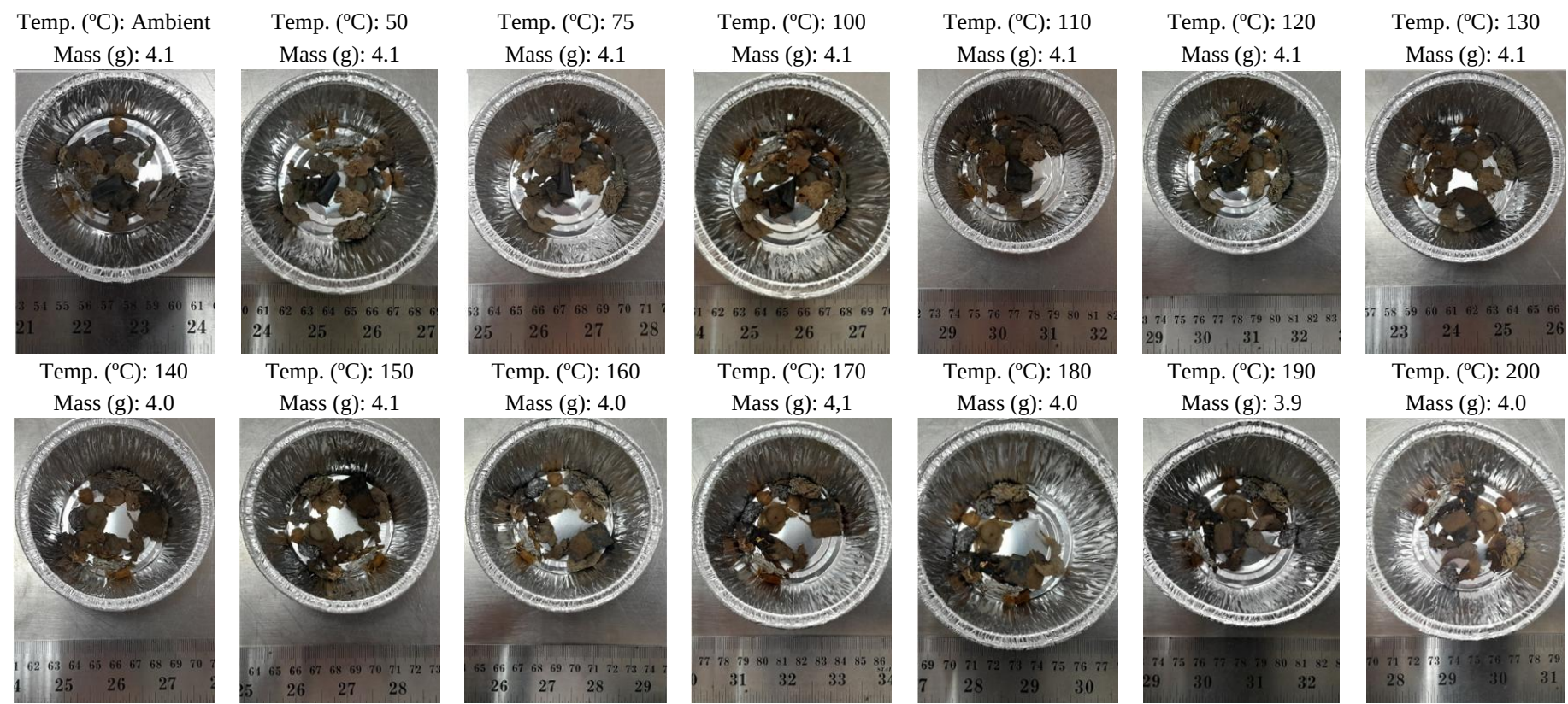


Figure A.3.2 - Sample A – Discarded materials – Non floating solids

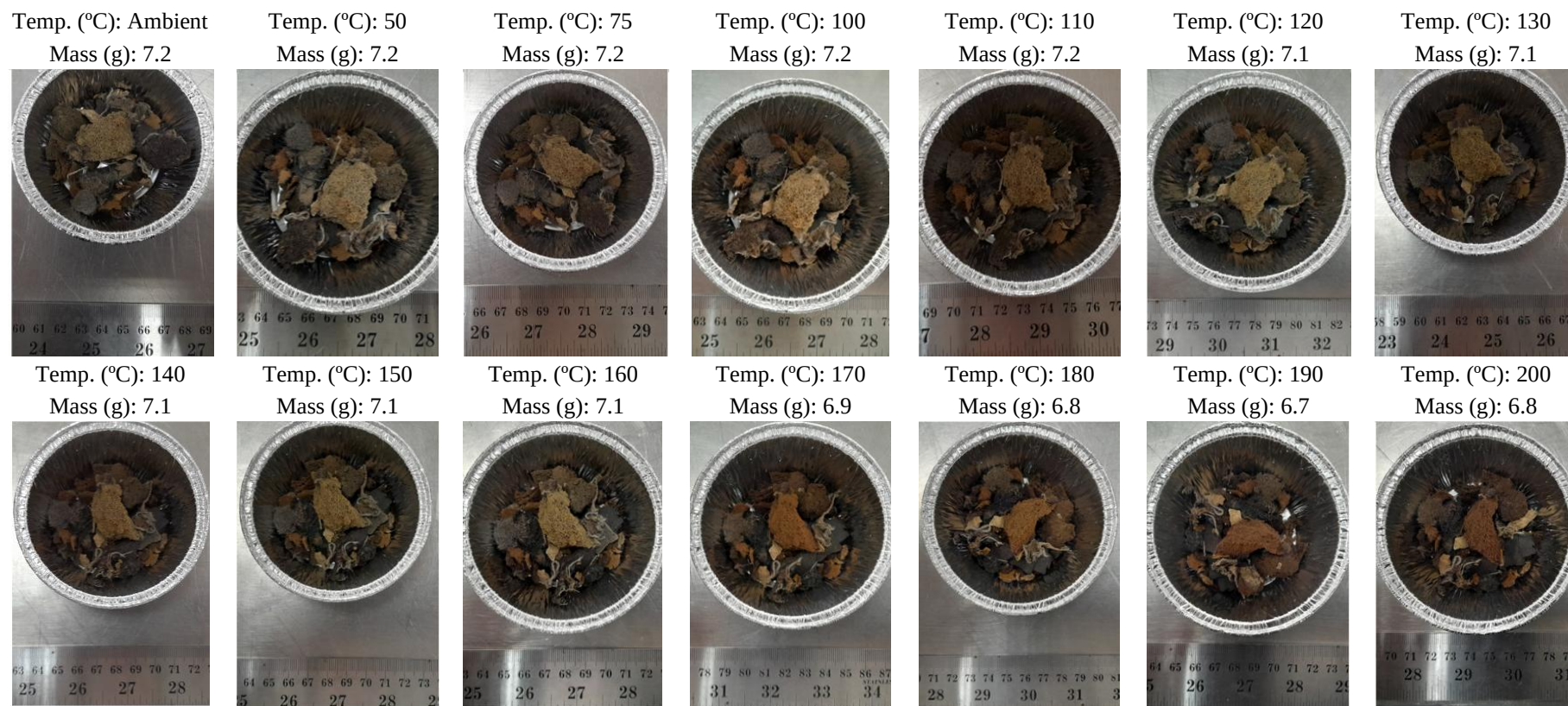


Figure A.3.3 - Sample A - Sponge

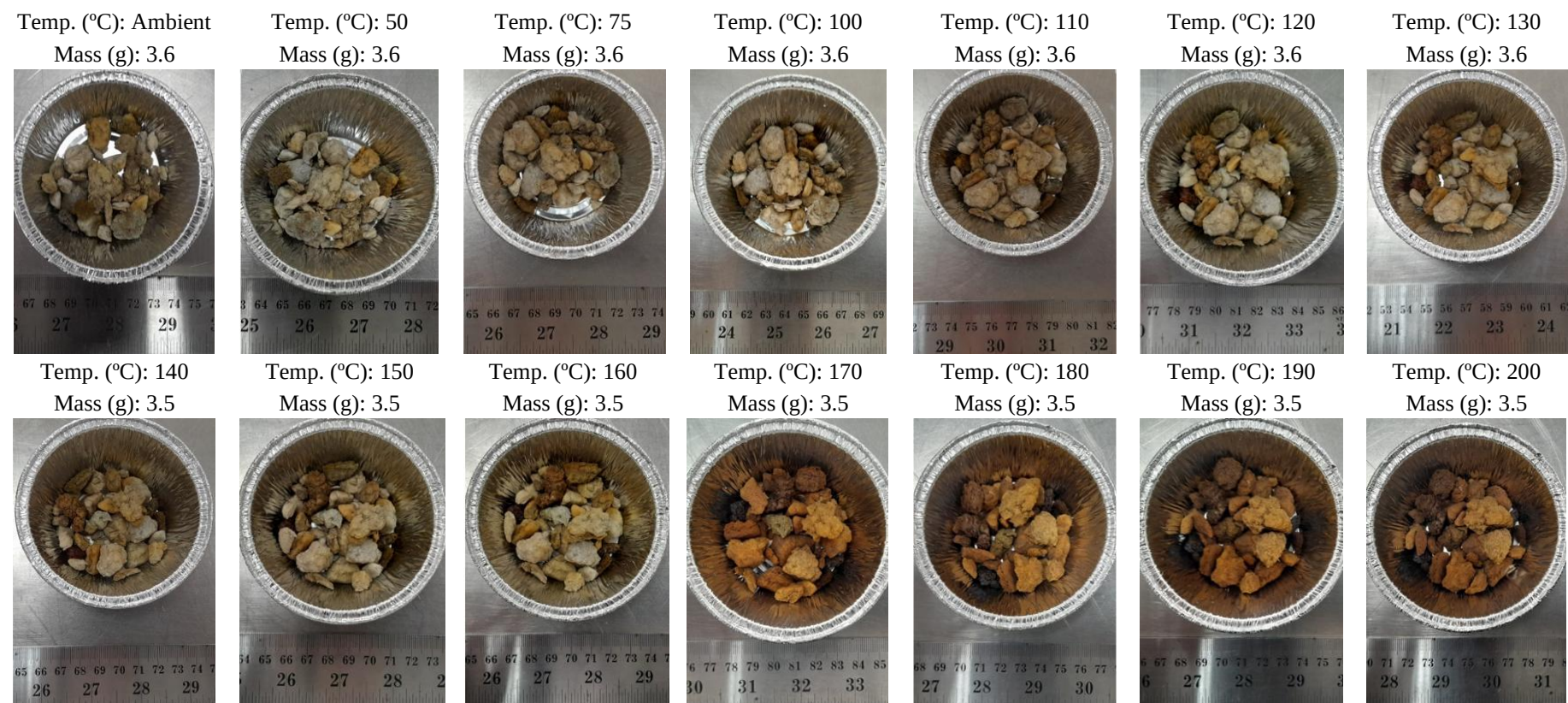


Figure A.3.4 - Sample A-Polyurethane

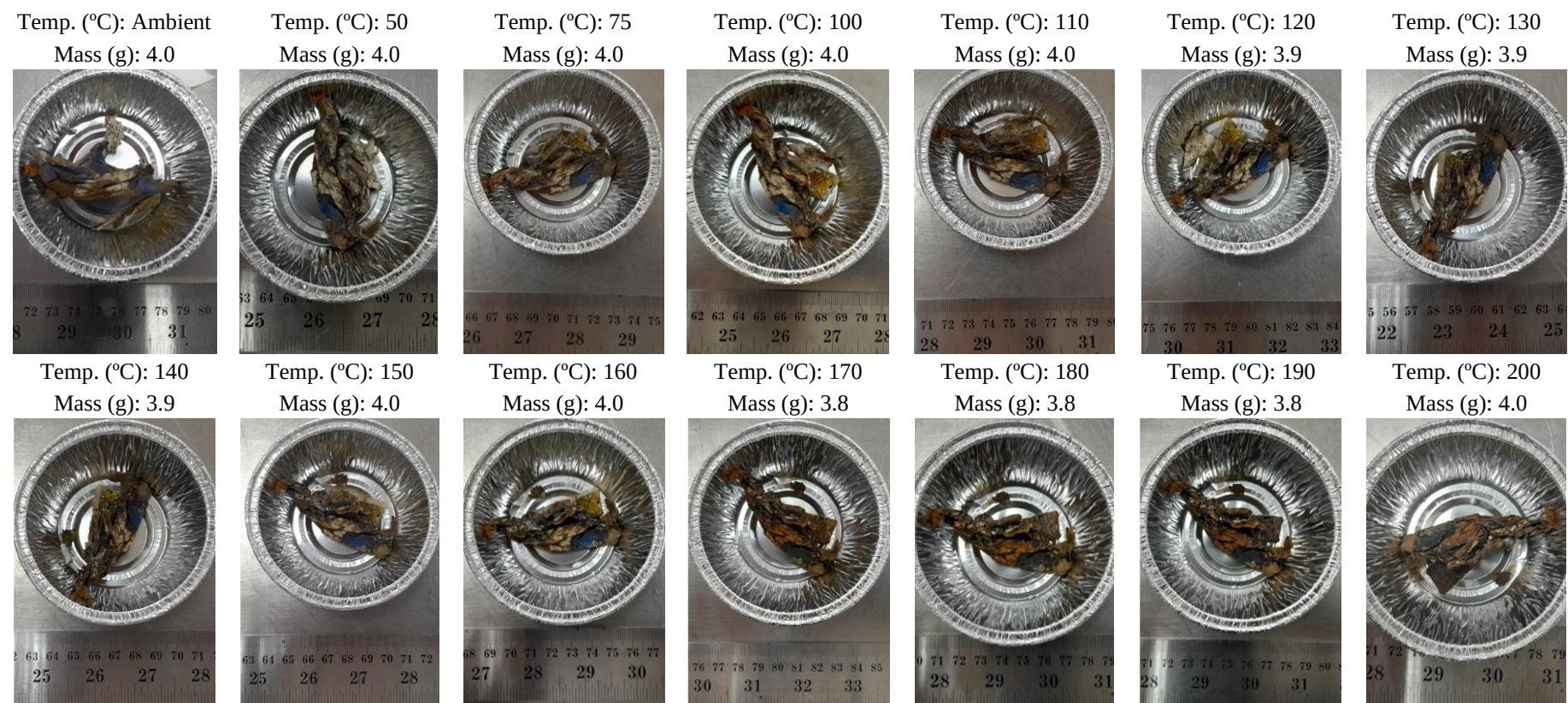


Figure A.3.5 - Sample A-Paper

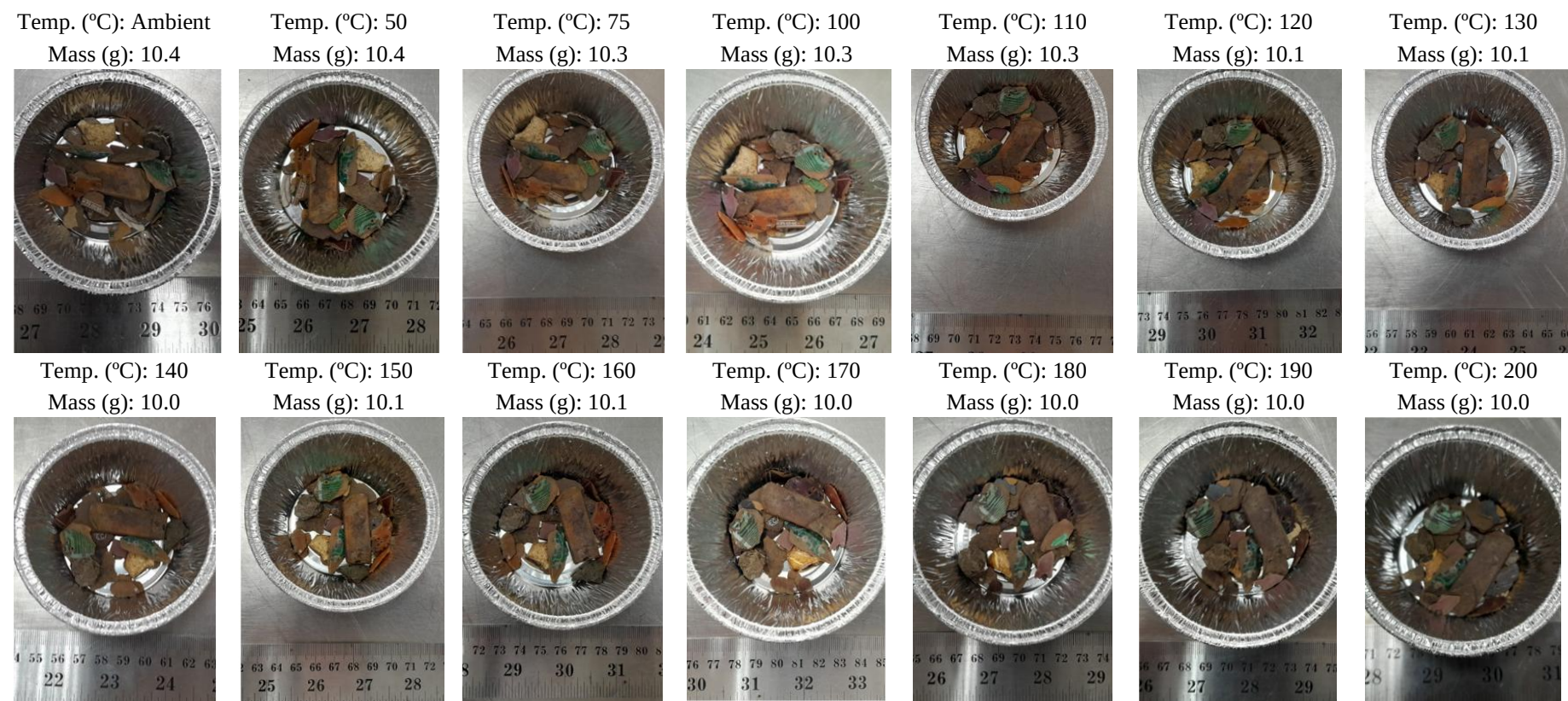


Figure A.3.6 - Sample A - Microchips

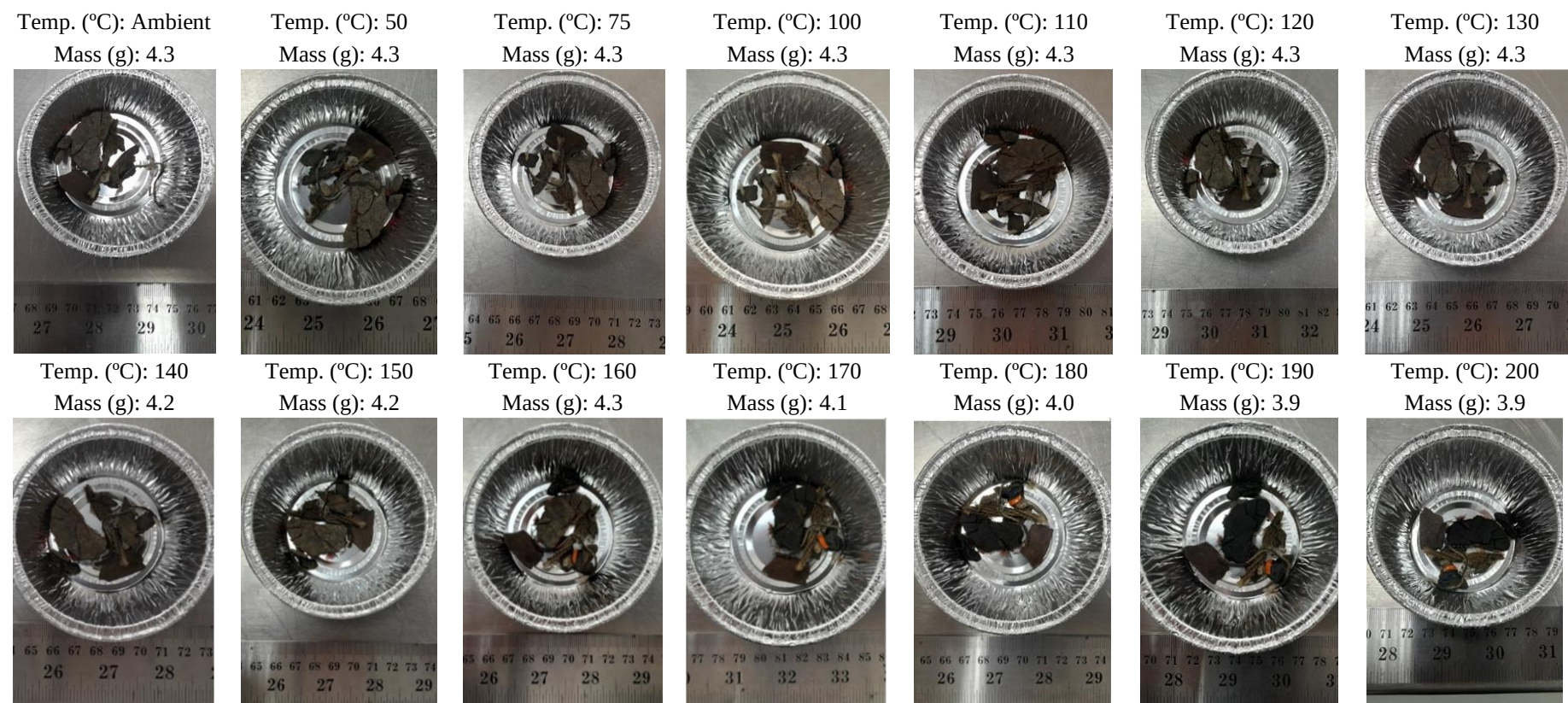


Figure A.3.7 - Sample A – Floating tyre rubber

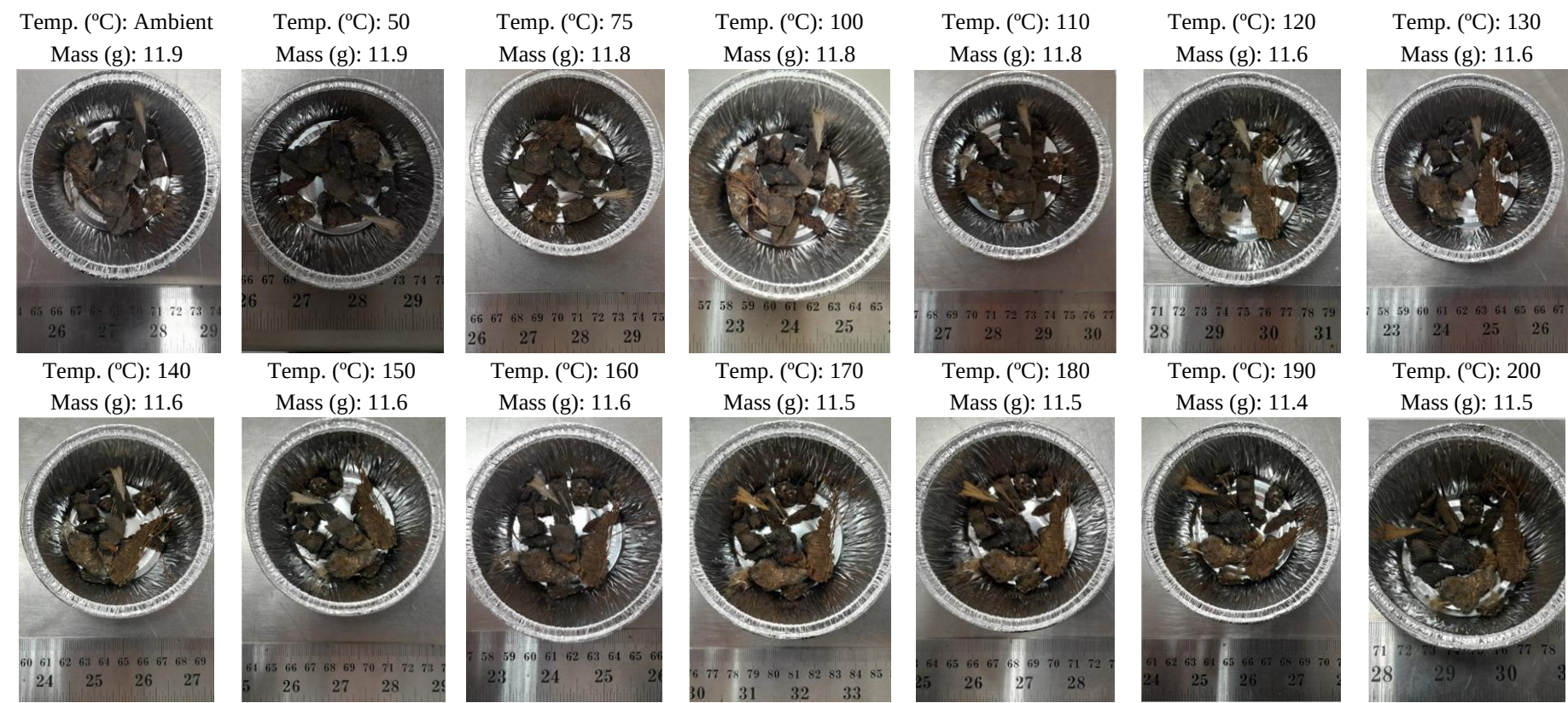


Figure A.3.8 - Sample A – Non floating tyre rubber

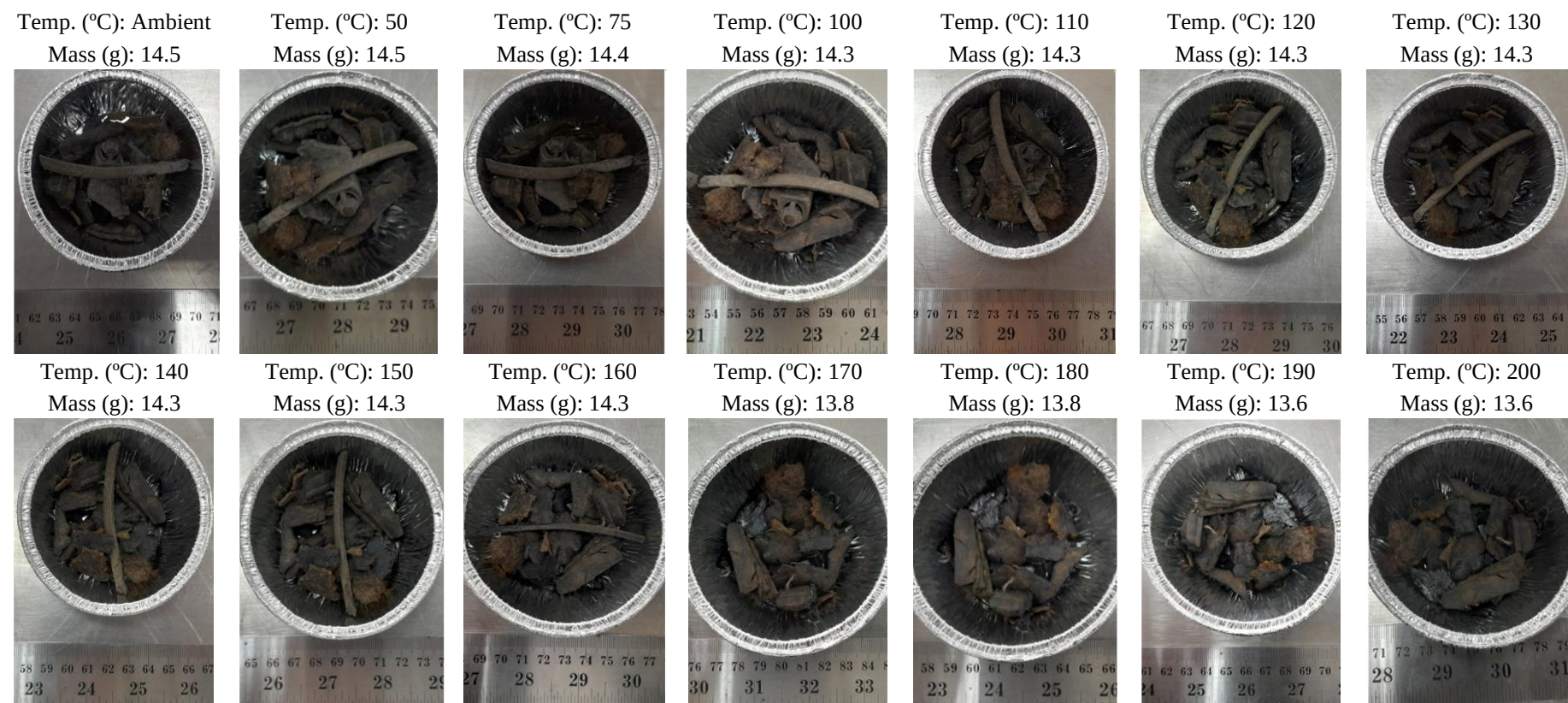


Figure A.3.9 - Sample A – Floating rubber

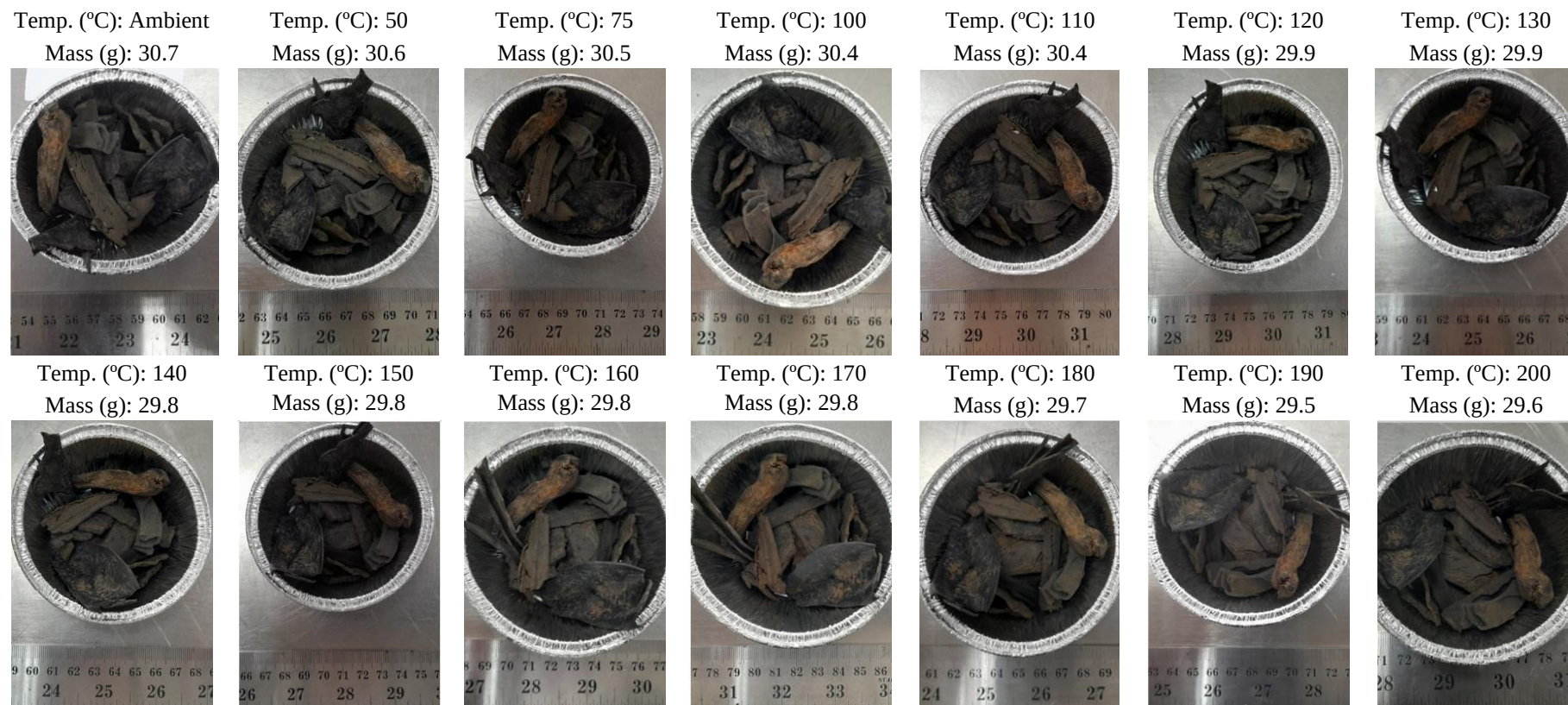


Figure A.3.10 - Sample A – Non floating rubber

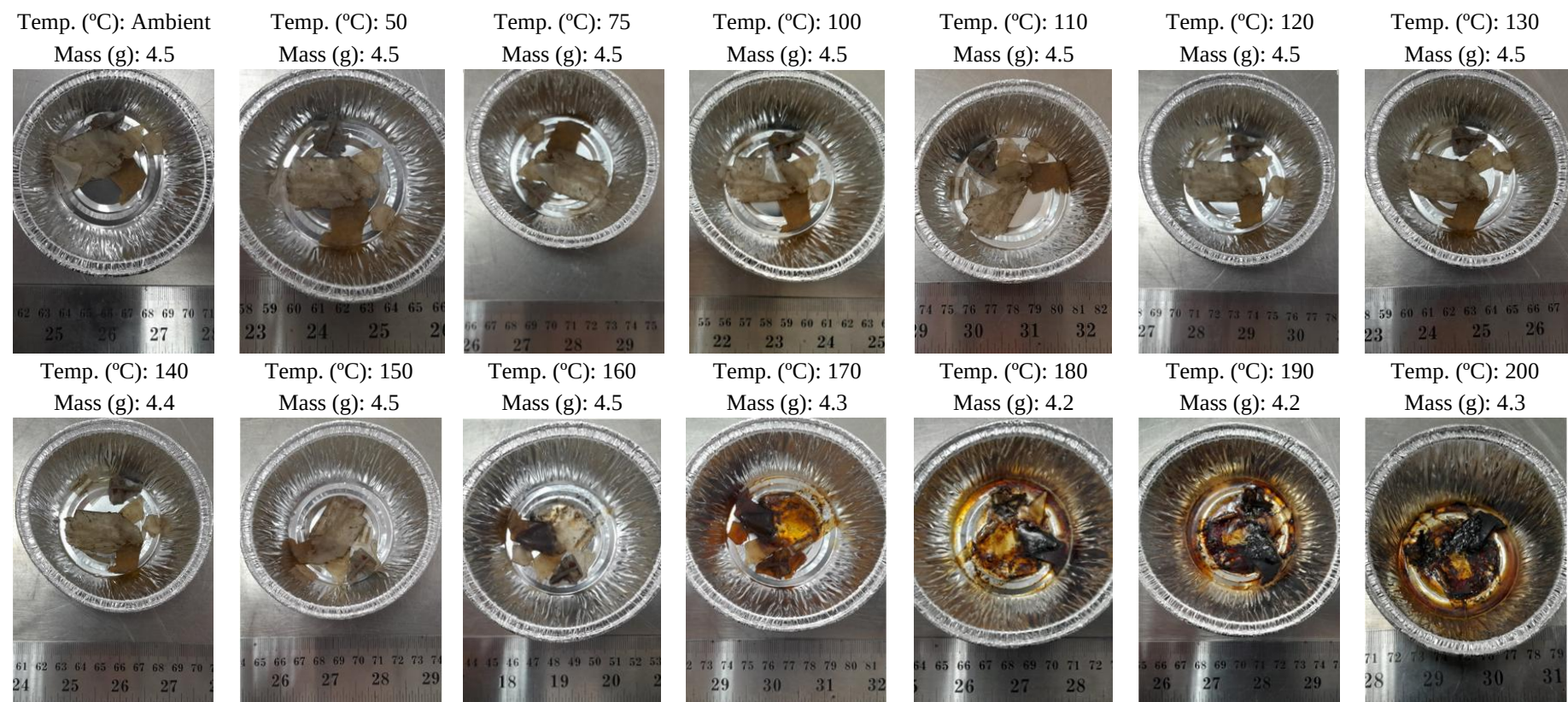


Figure A.3.11 - Sample A - Floating transparent plastics

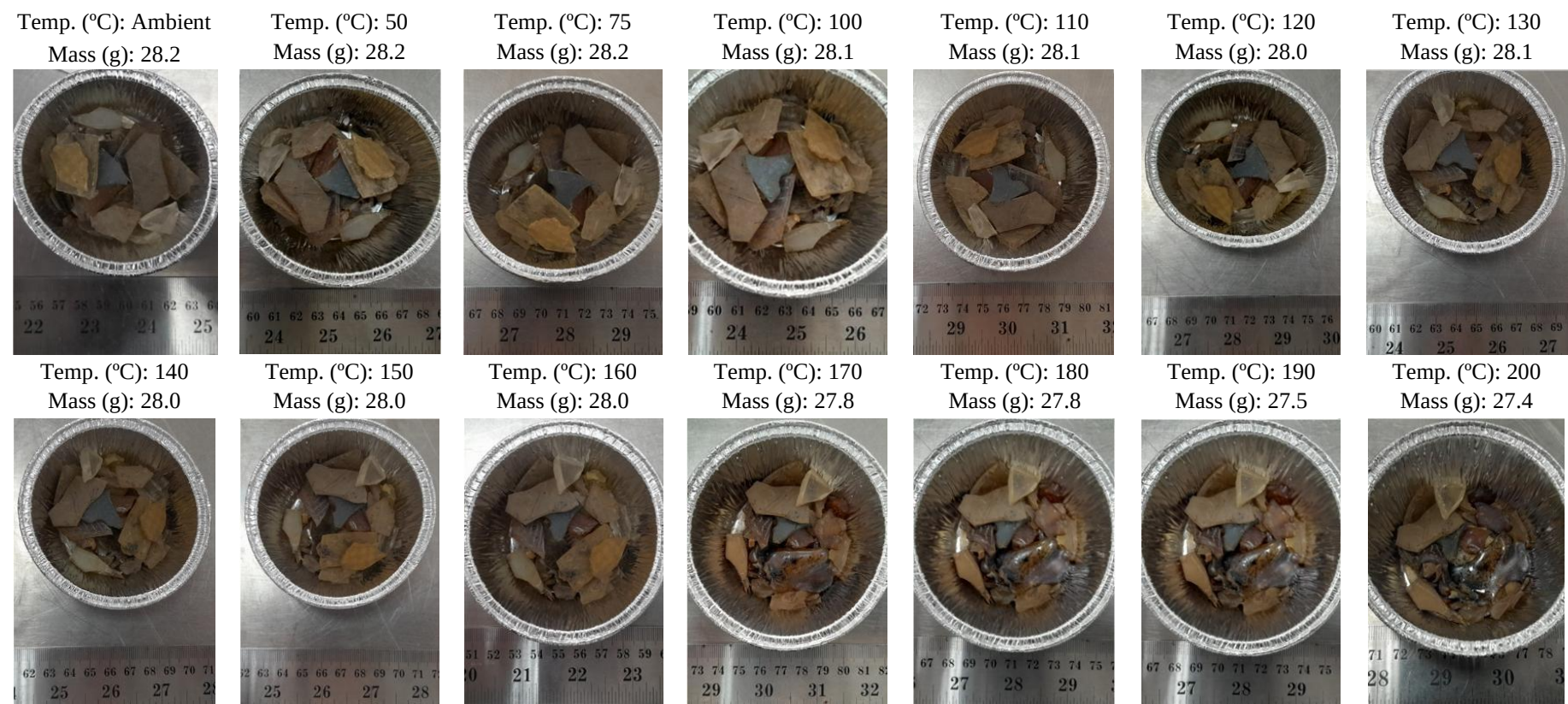


Figure A.3.12-Sample A - Non floating transparent plastics

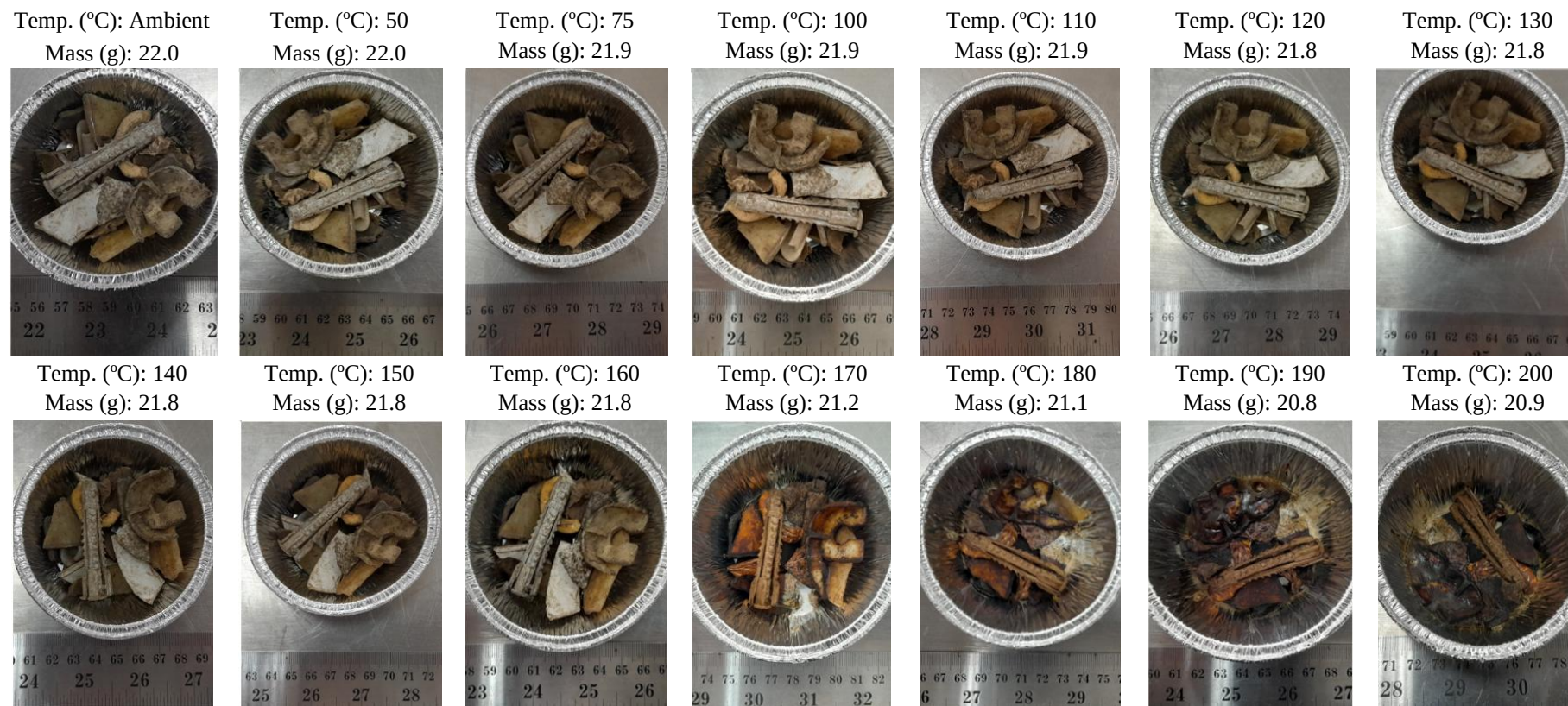


Figure A.3.13 - Sample A – Floating white plastics



Figure A.3.14 - Sample A – Non floating white plastics

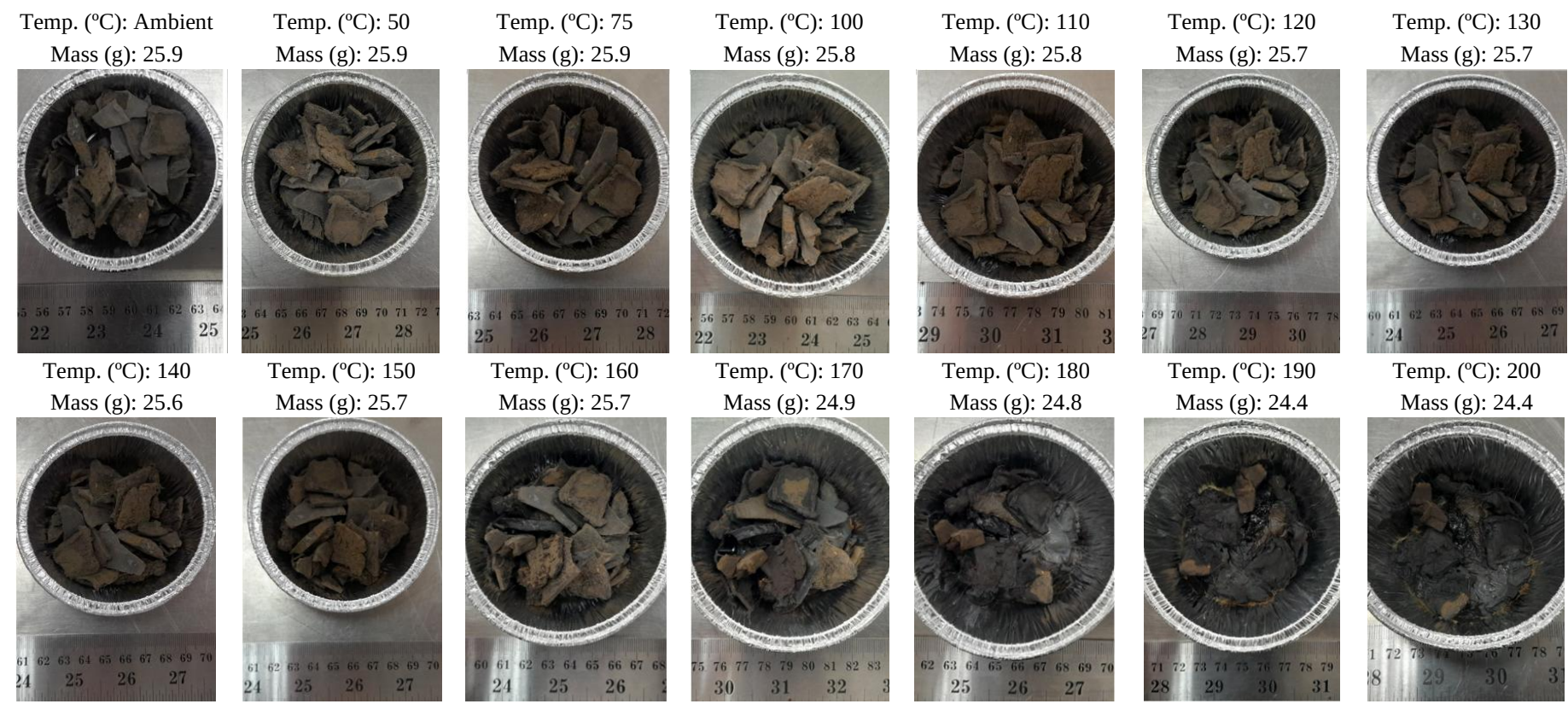


Figure A.3.15 - Sample A – Floating black plastic



Figure A.3.16 - Sample A – Non floating black plastic

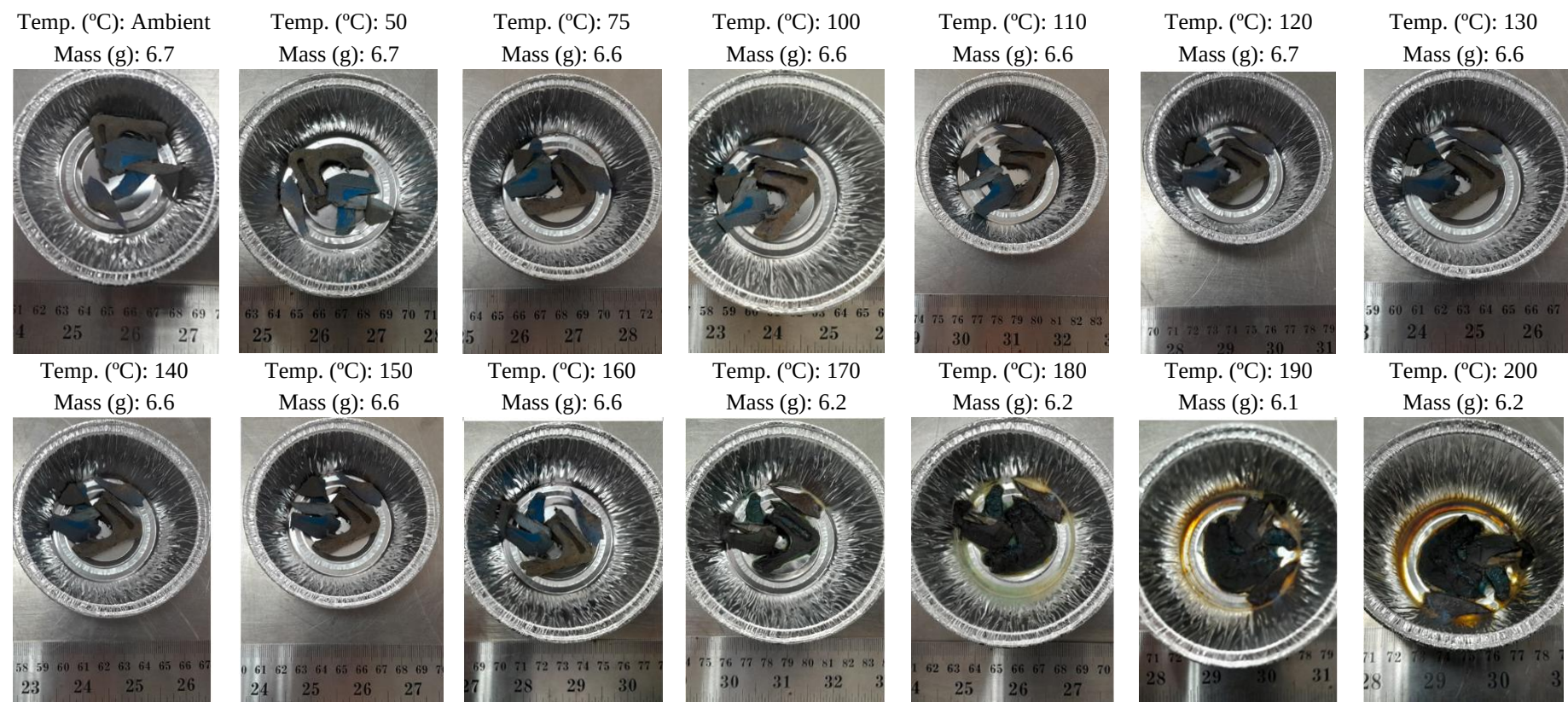


Figure A.3.17 - Sample A – Floating blue and yellow plastics

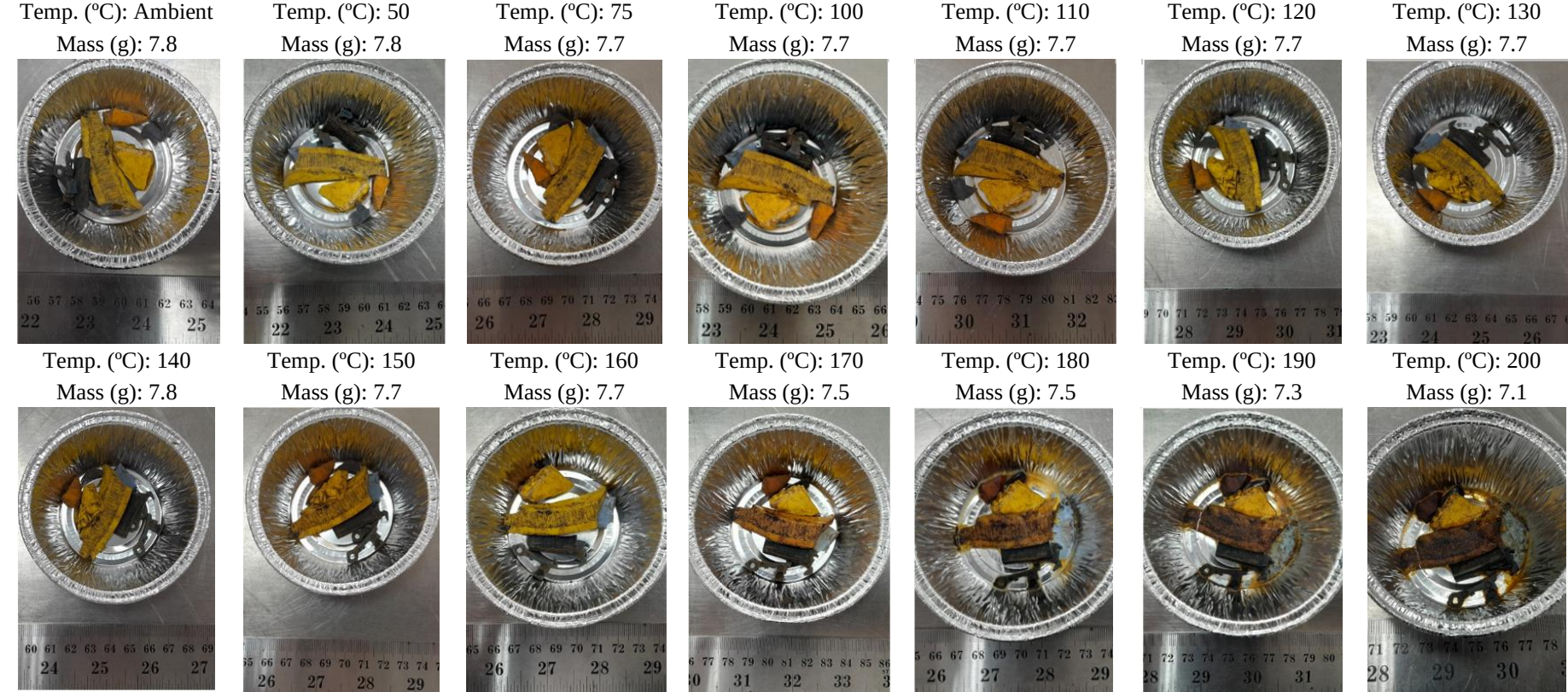


Figure A.3.18 - Sample A – Non floating blue and yellow plastics

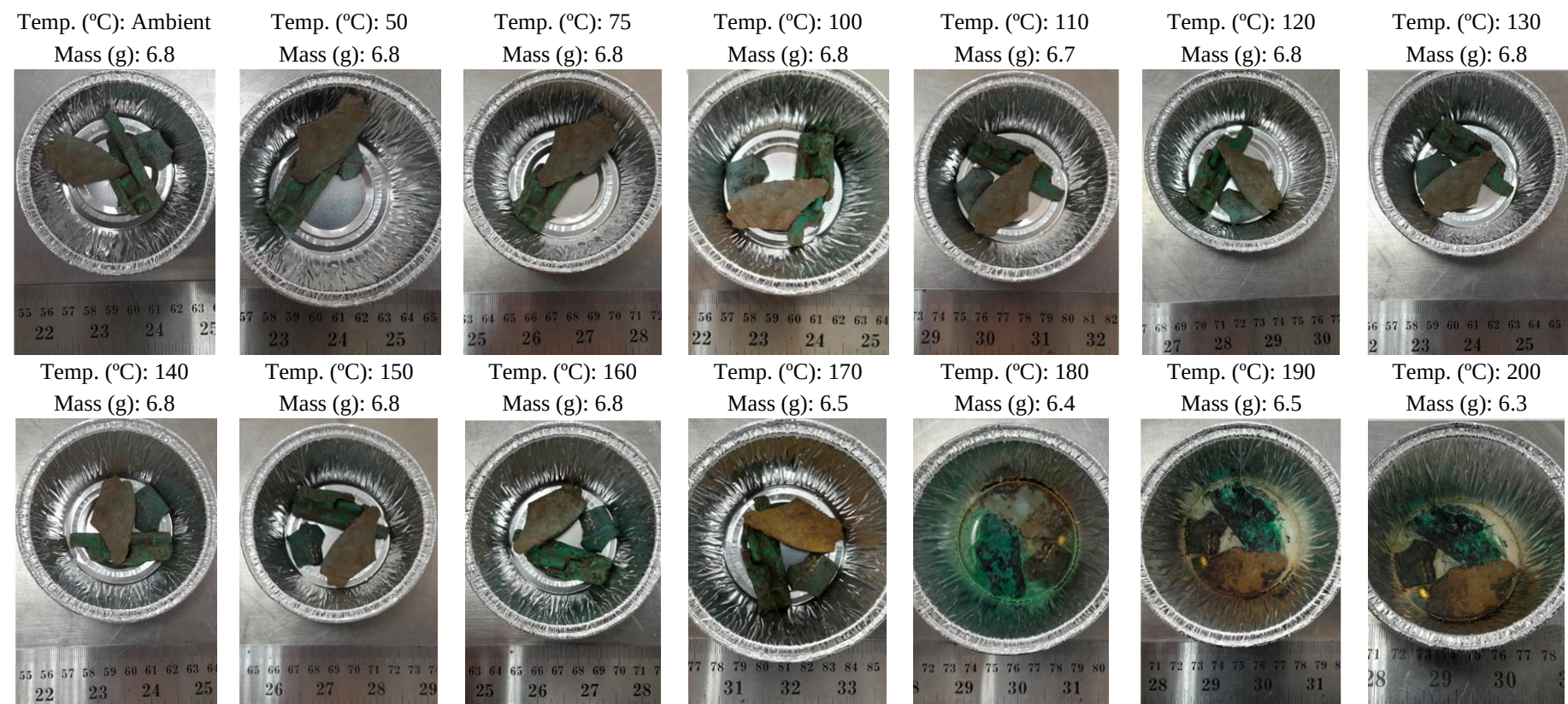


Figure A.3.19 - Sample A – Floating green plastic

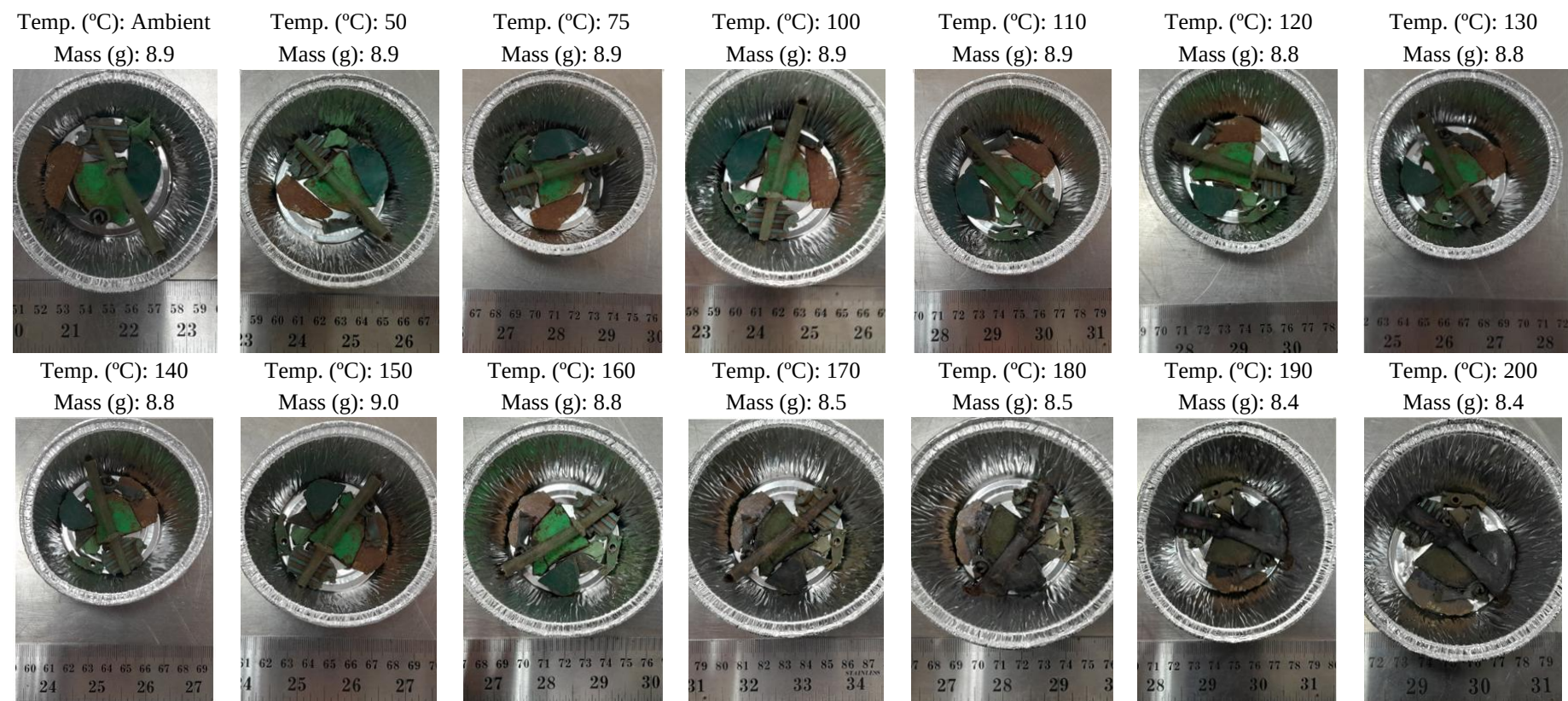


Figure A.3.20 - Sample A – Non floating green plastic

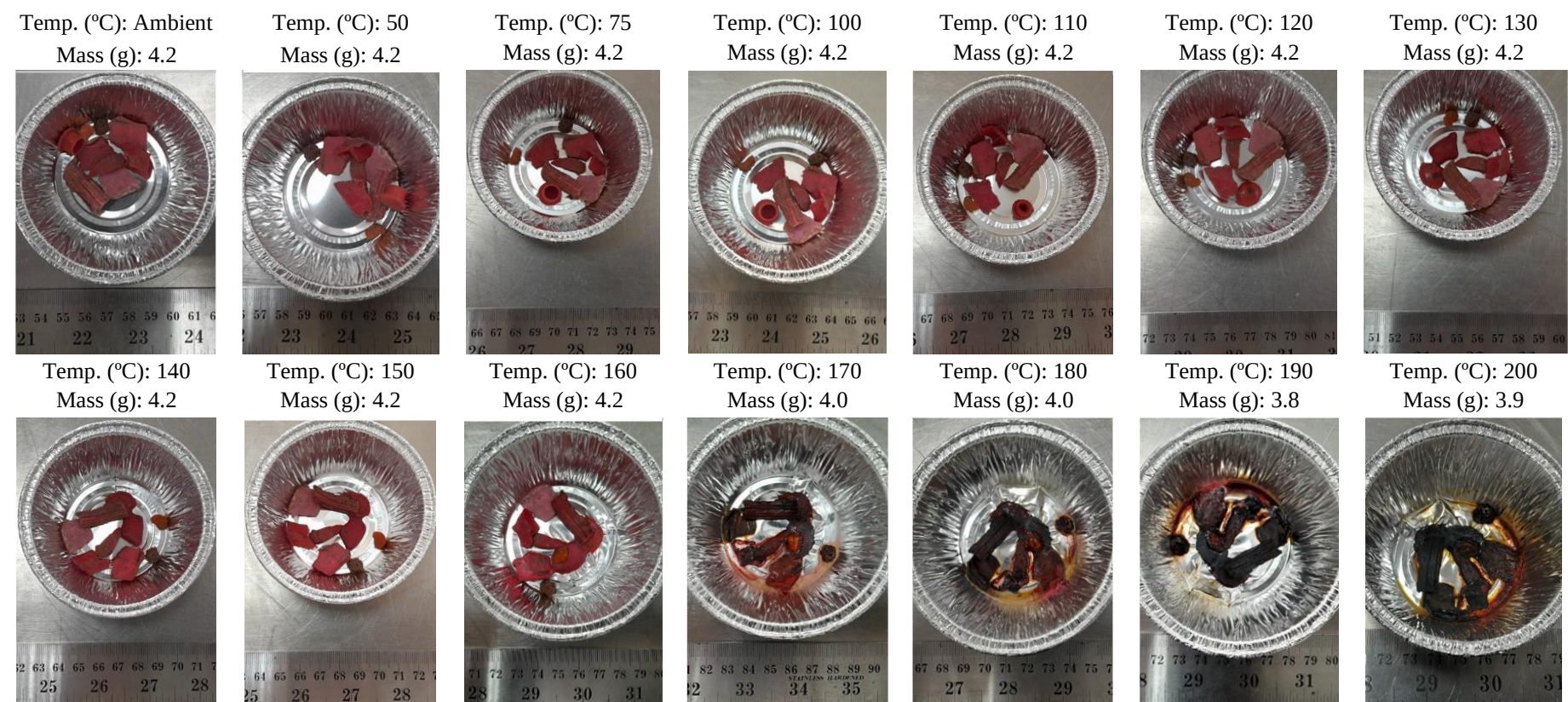


Figure A.3.21 - Sample A – Floating red plastics

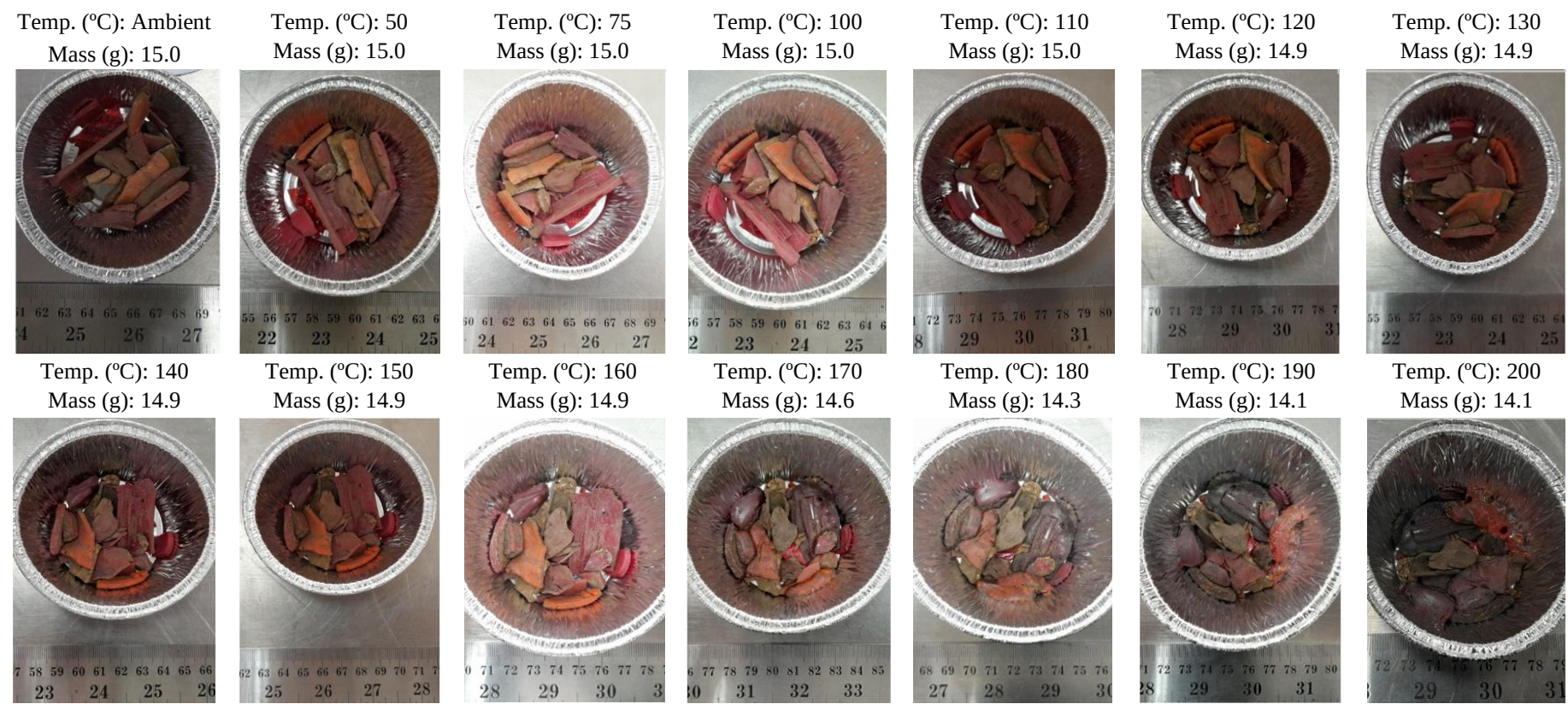


Figure A.3.22 - Sample A – Non floating red plastics

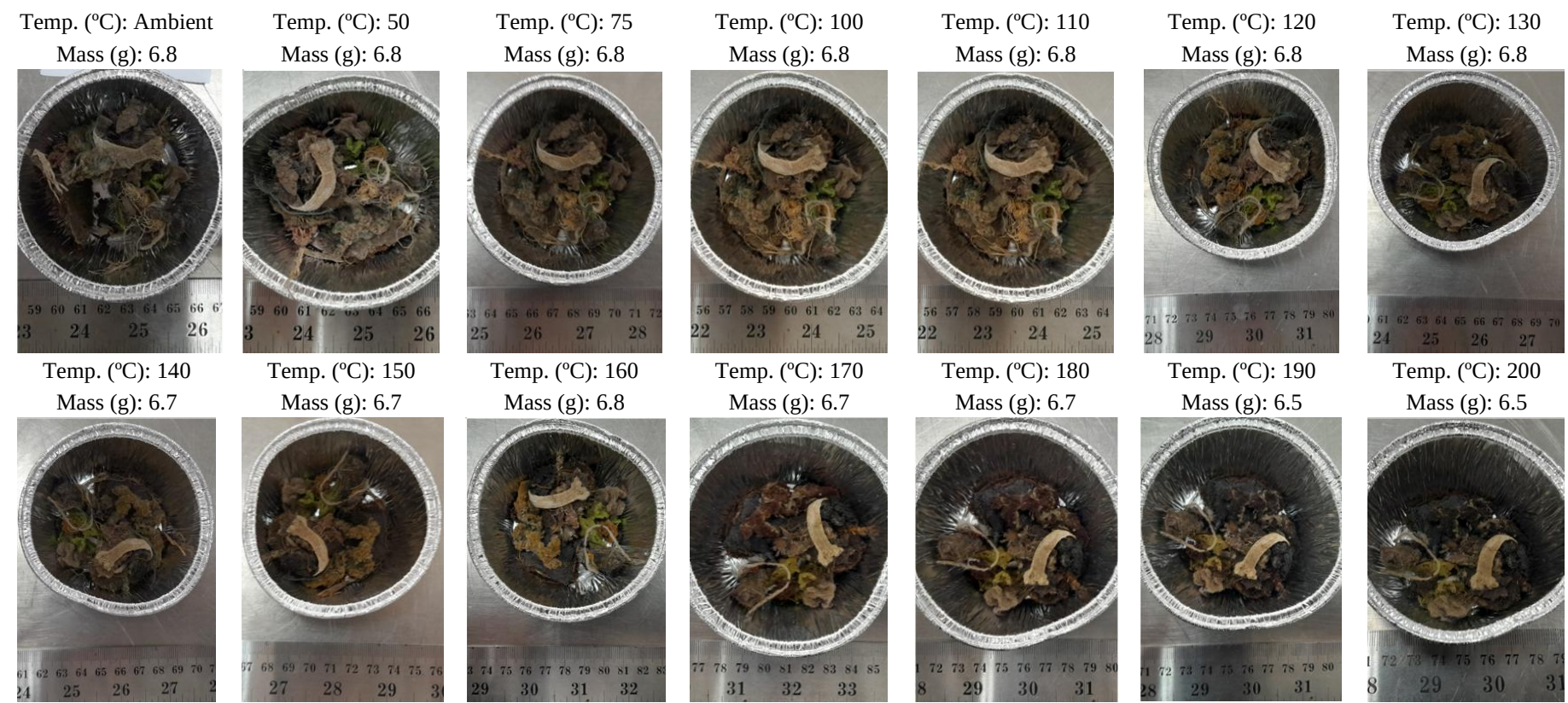


Figure A.3.23 - Sample A – Floating fabrics

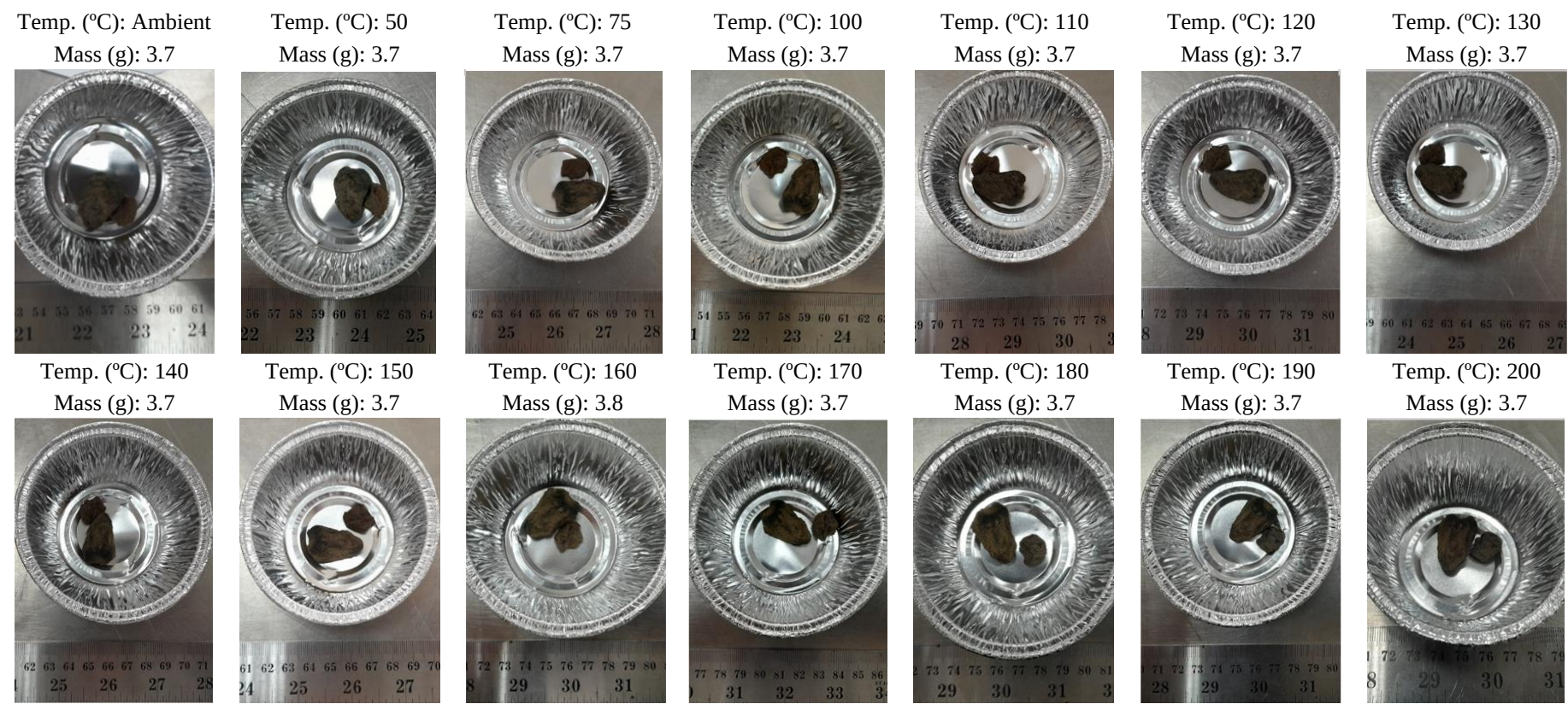


Figure A.3.24 - Sample A – Floating unknown

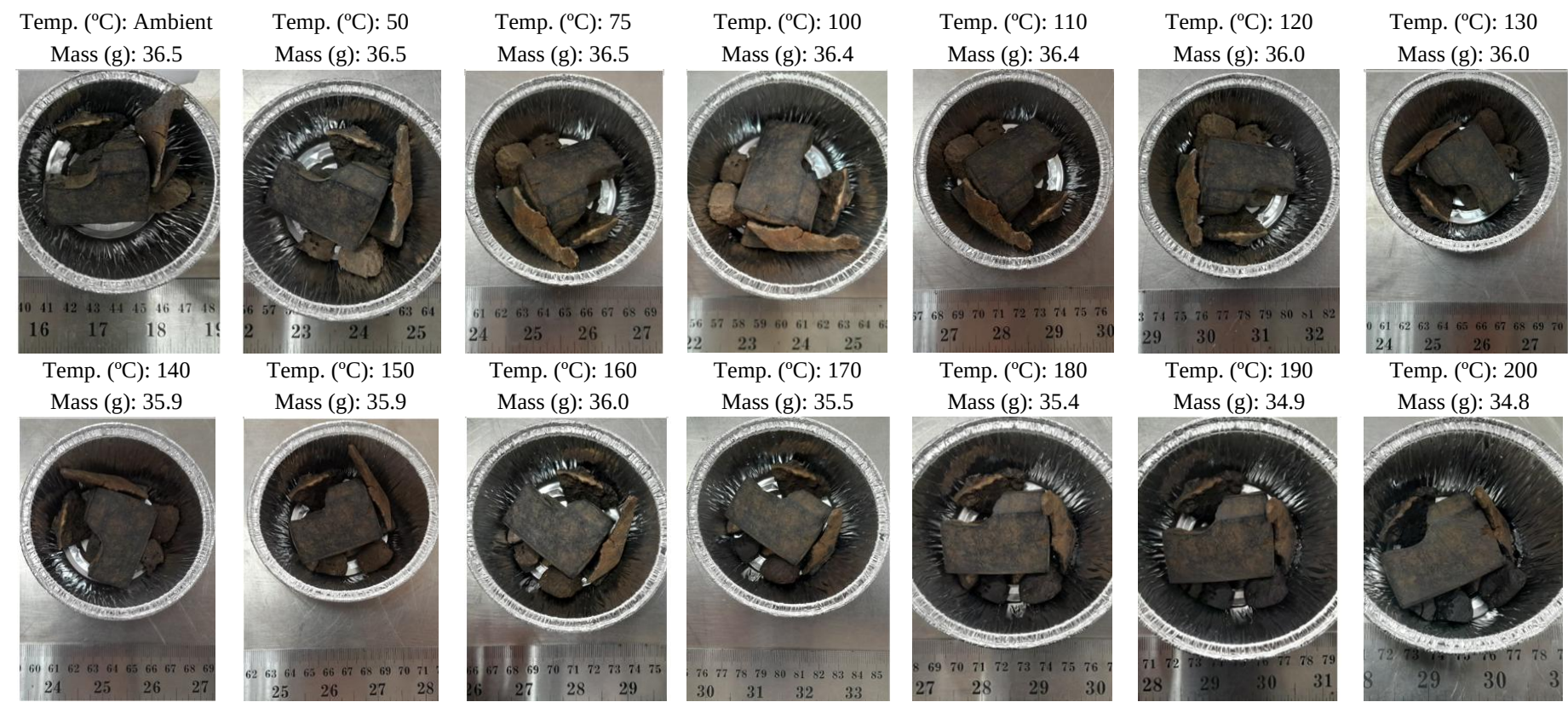


Figure A.3.25 - Sample A – Non floating unknown

Annex 4: Melting point of sample B

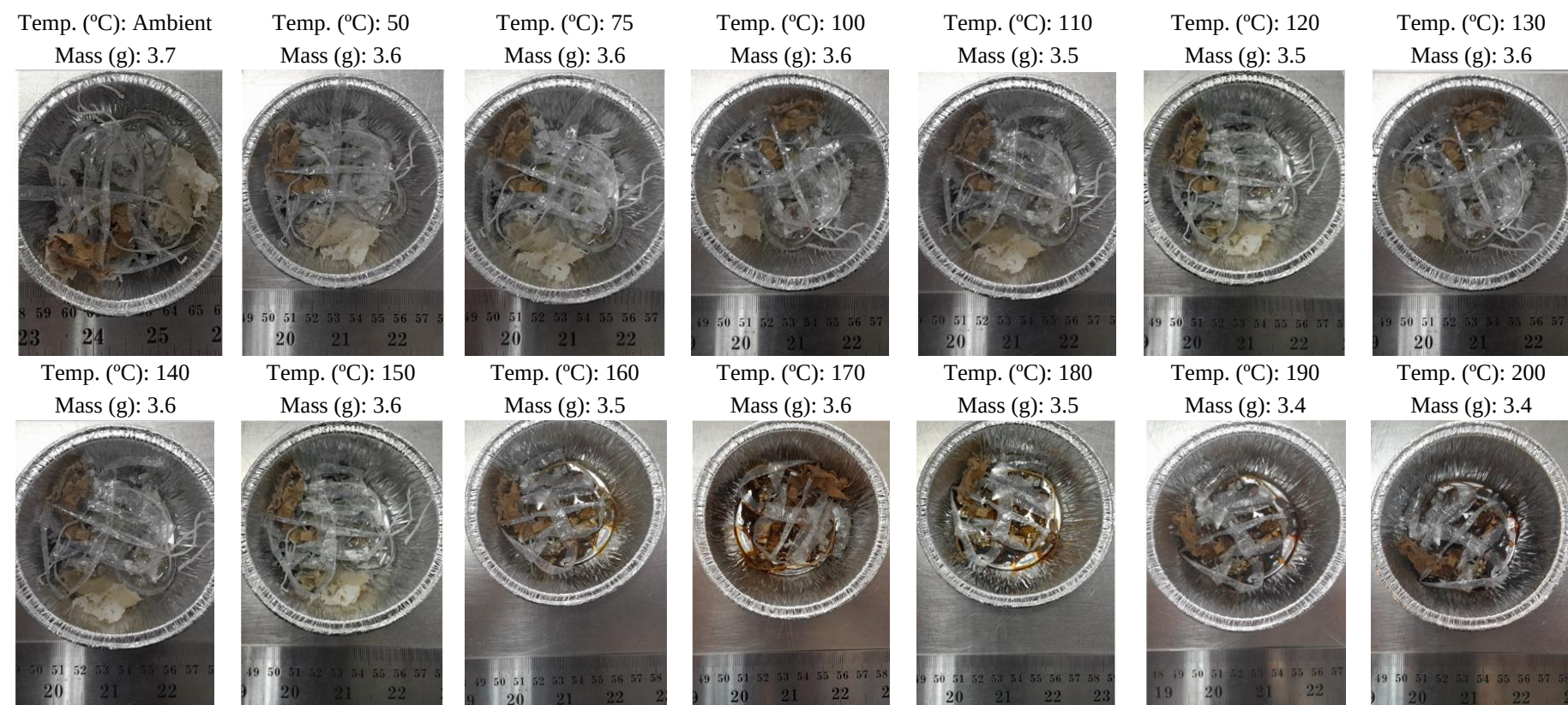


Figure A.4.1 - Sample B – Floating shredded plastic bags

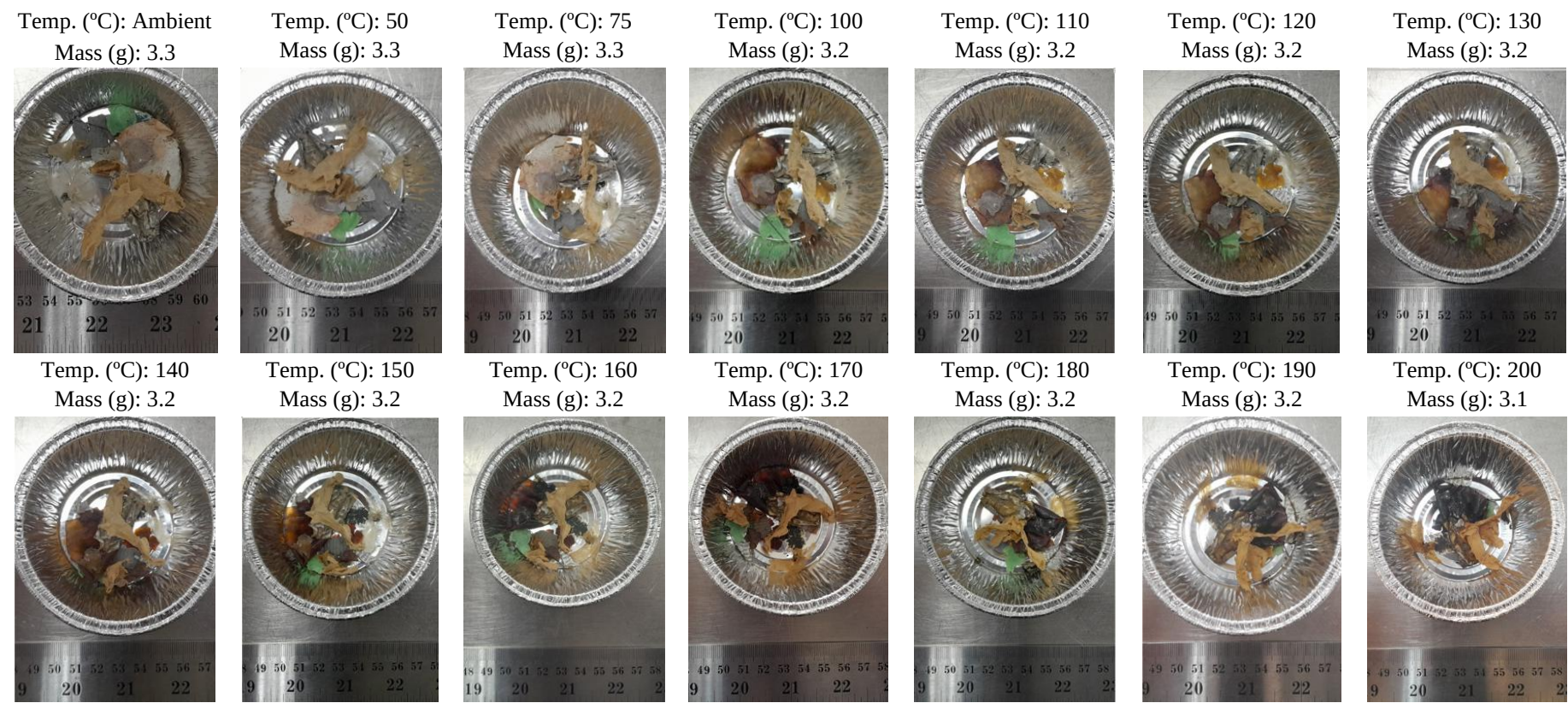


Figure A.4.2 - Sample B – Non floating shredded plastic bags

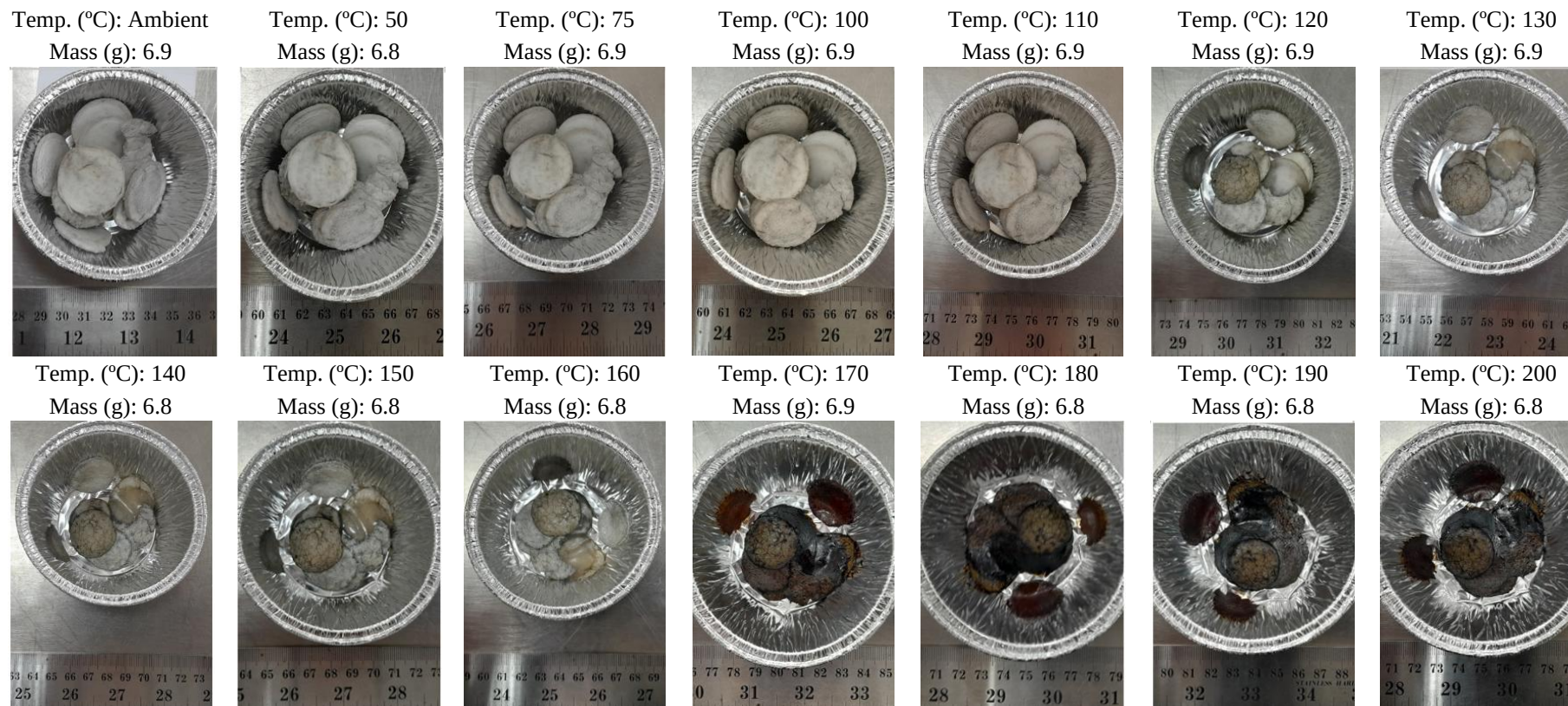


Figure A.4.3 - Sample B – Floating mixed paper capsules

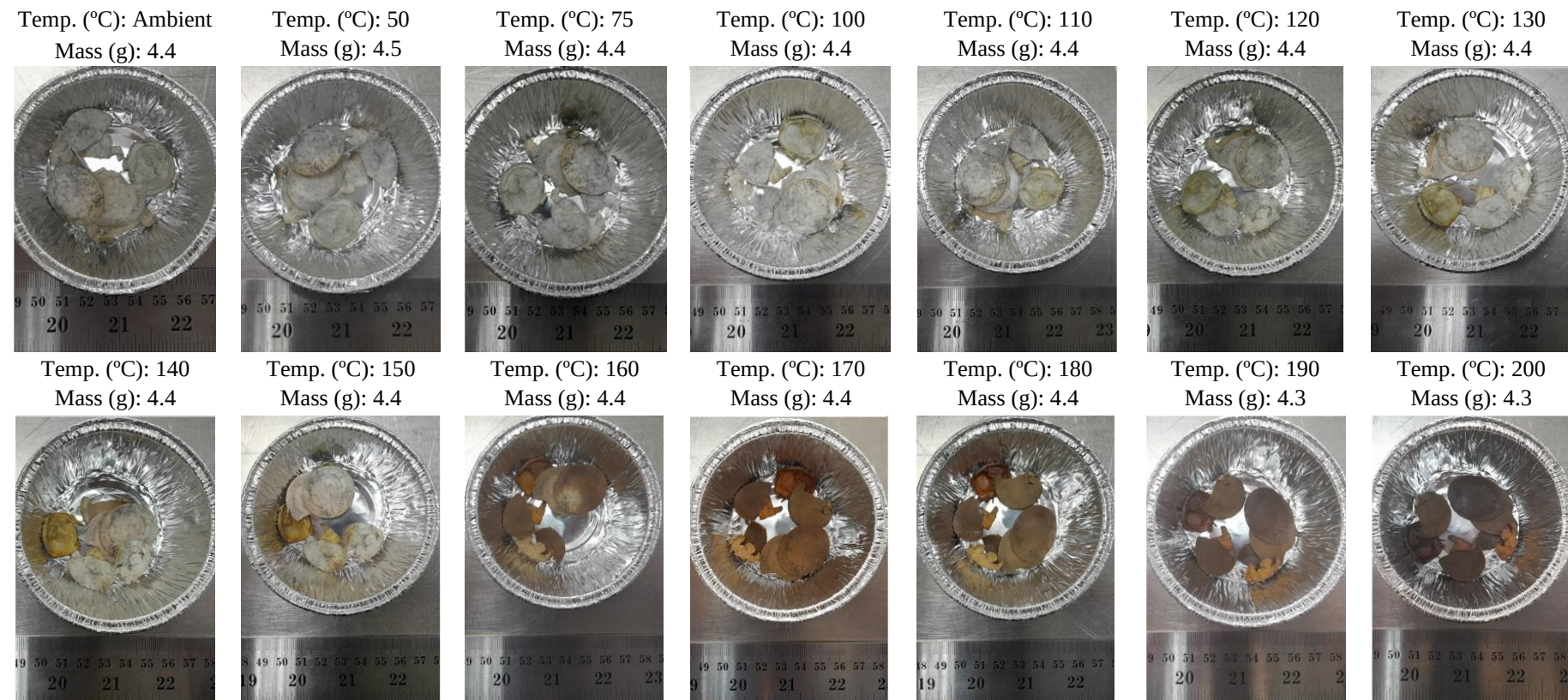


Figure A.4.4 - Sample B – Non floating mixed paper capsules

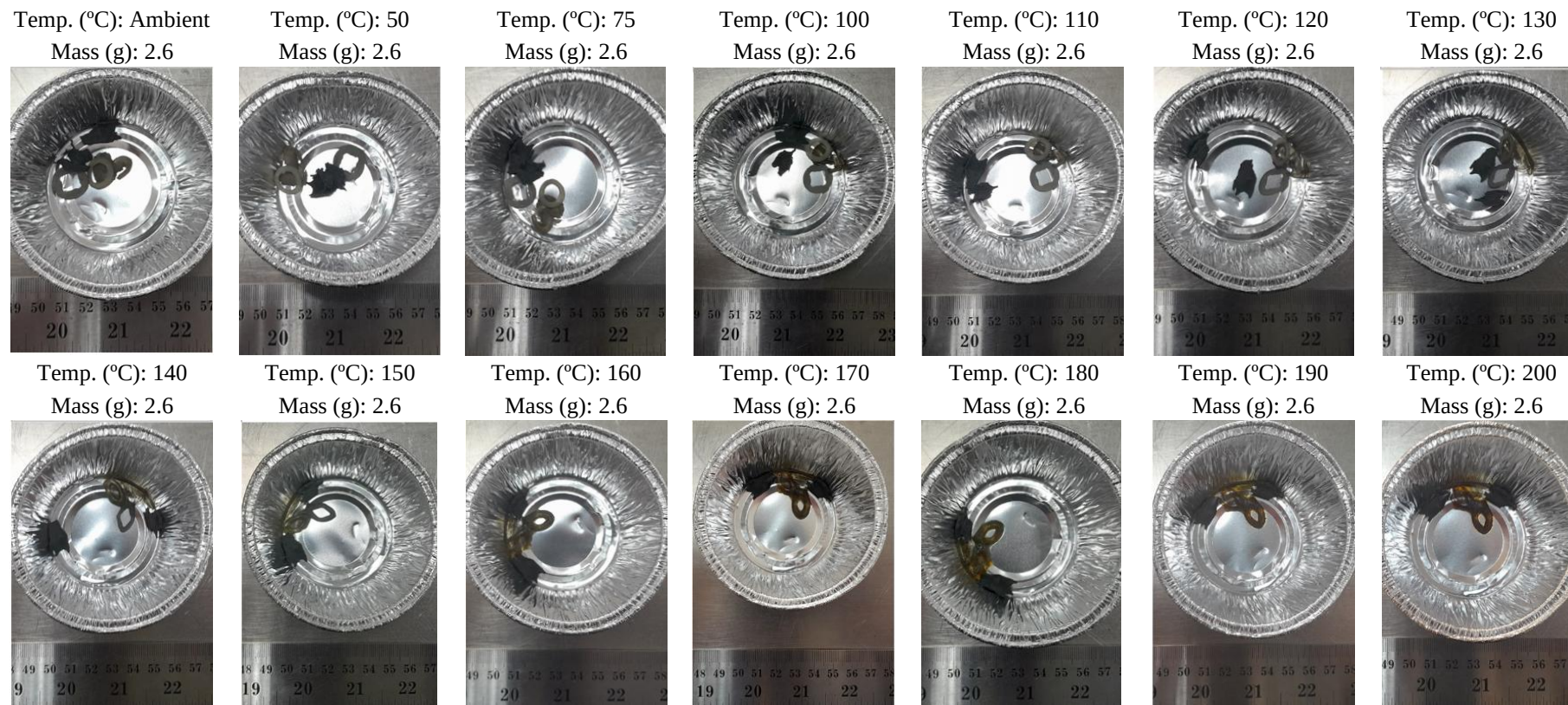


Figure A.4.5 - Sample B – Floating rubbers

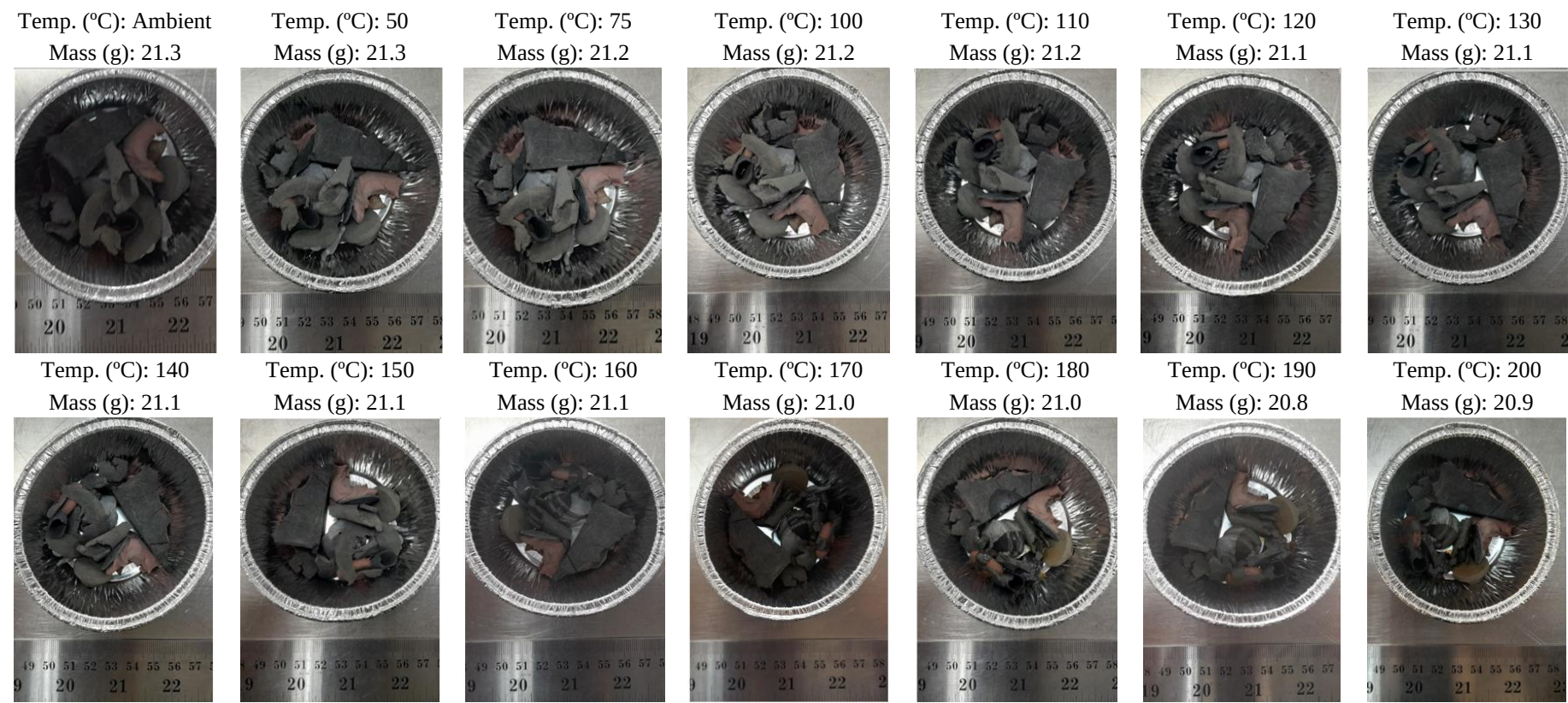


Figure A.4.6 - Sample B – Non floating rubbers

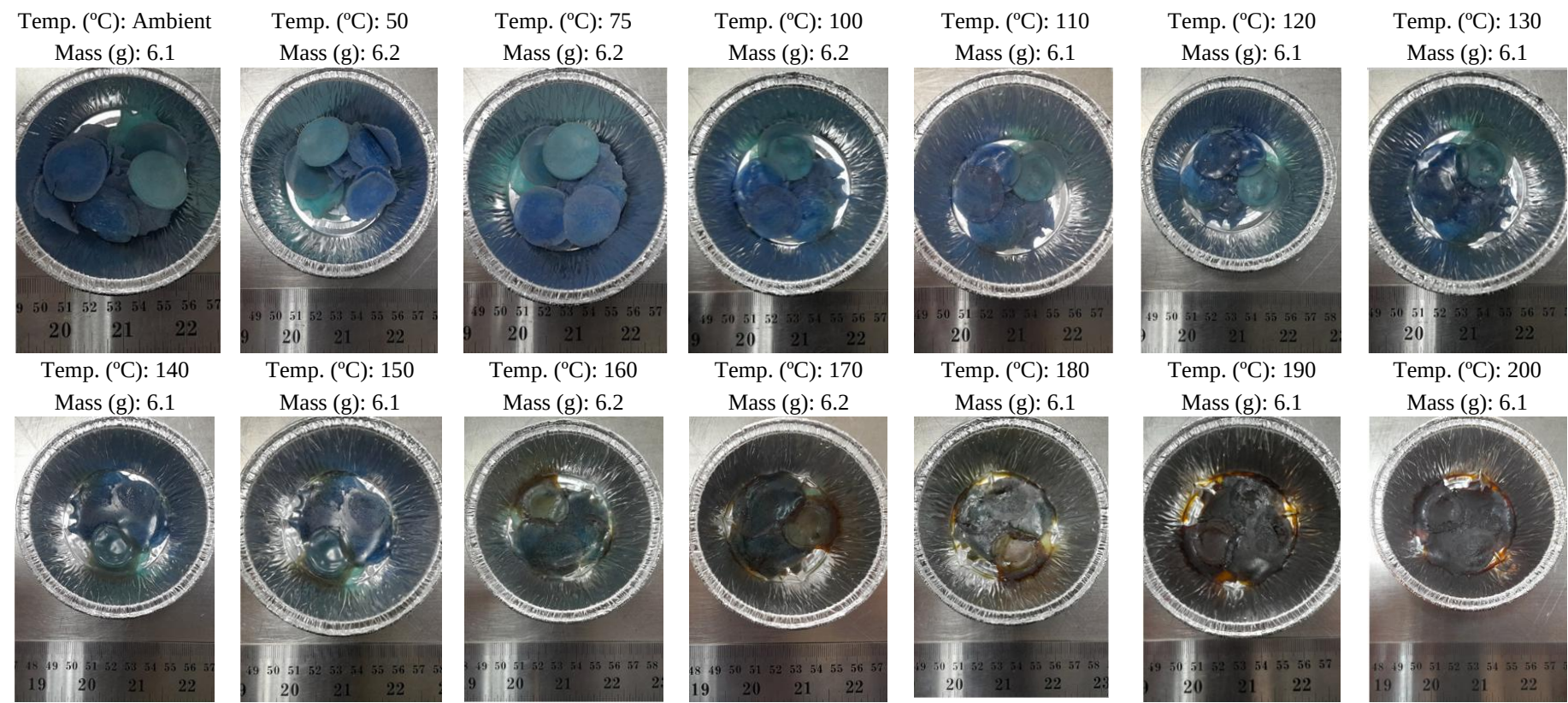


Figure A.4.7 - Sample B – Floating blue capsules

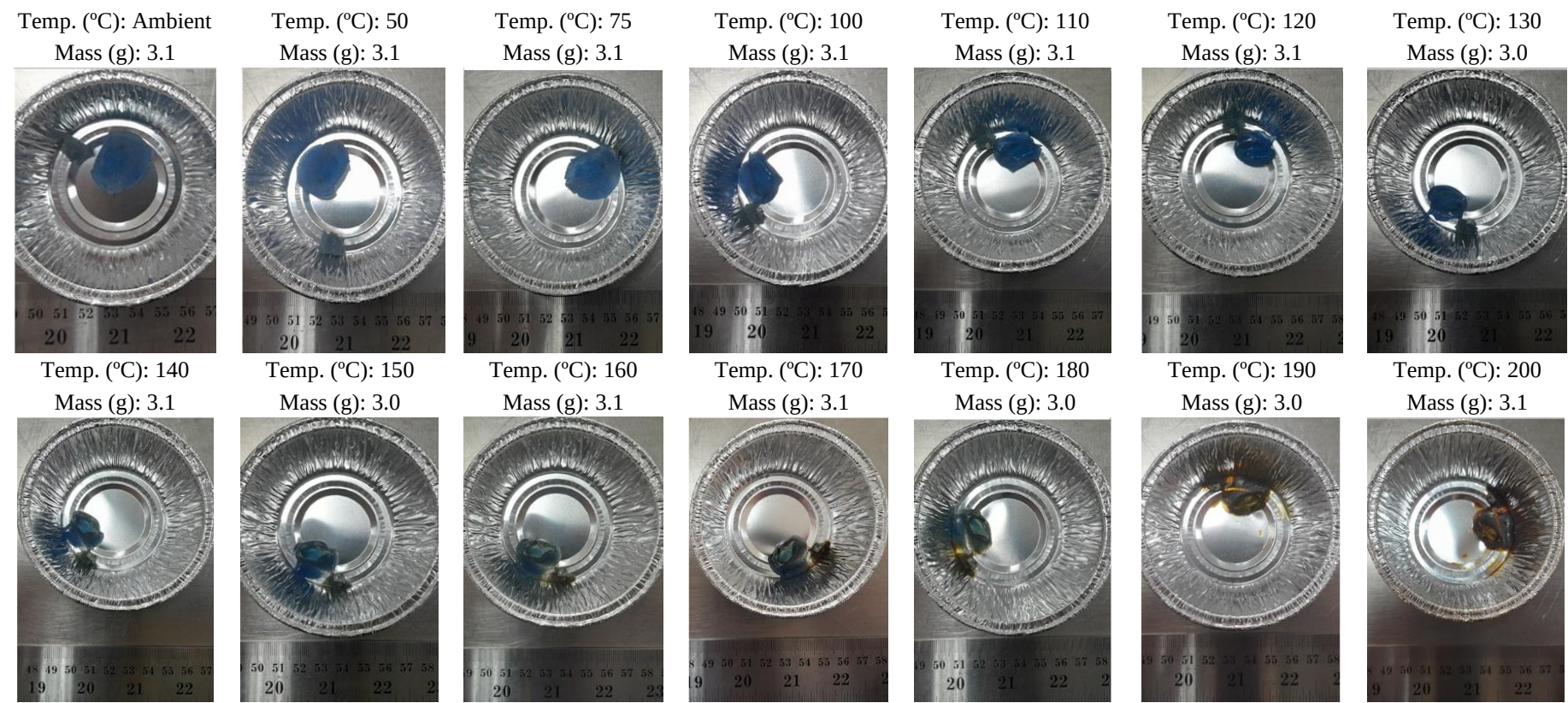


Figure A.4.8 - Sample B – Non floating blue capsules

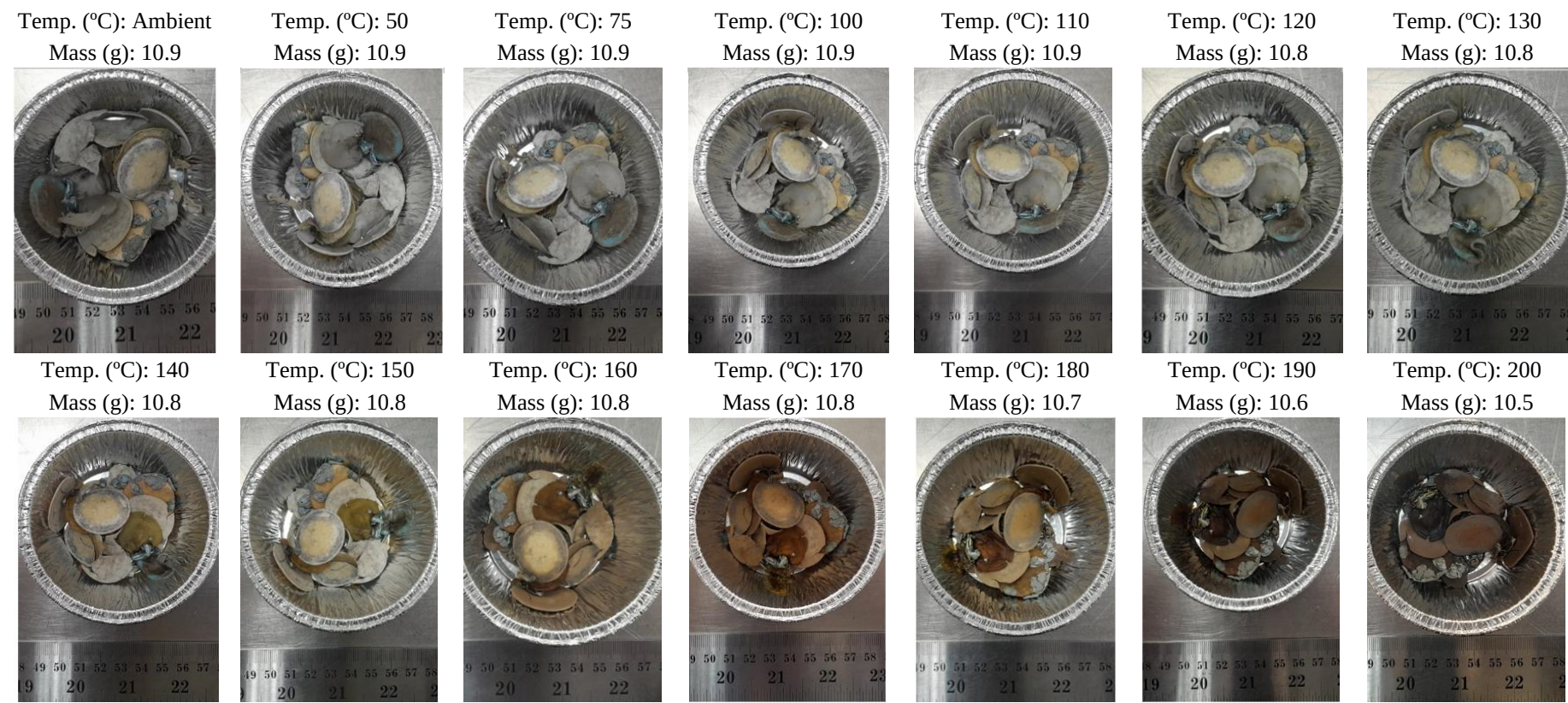


Figure A.4.9 - Sample B – Non floating white capsules

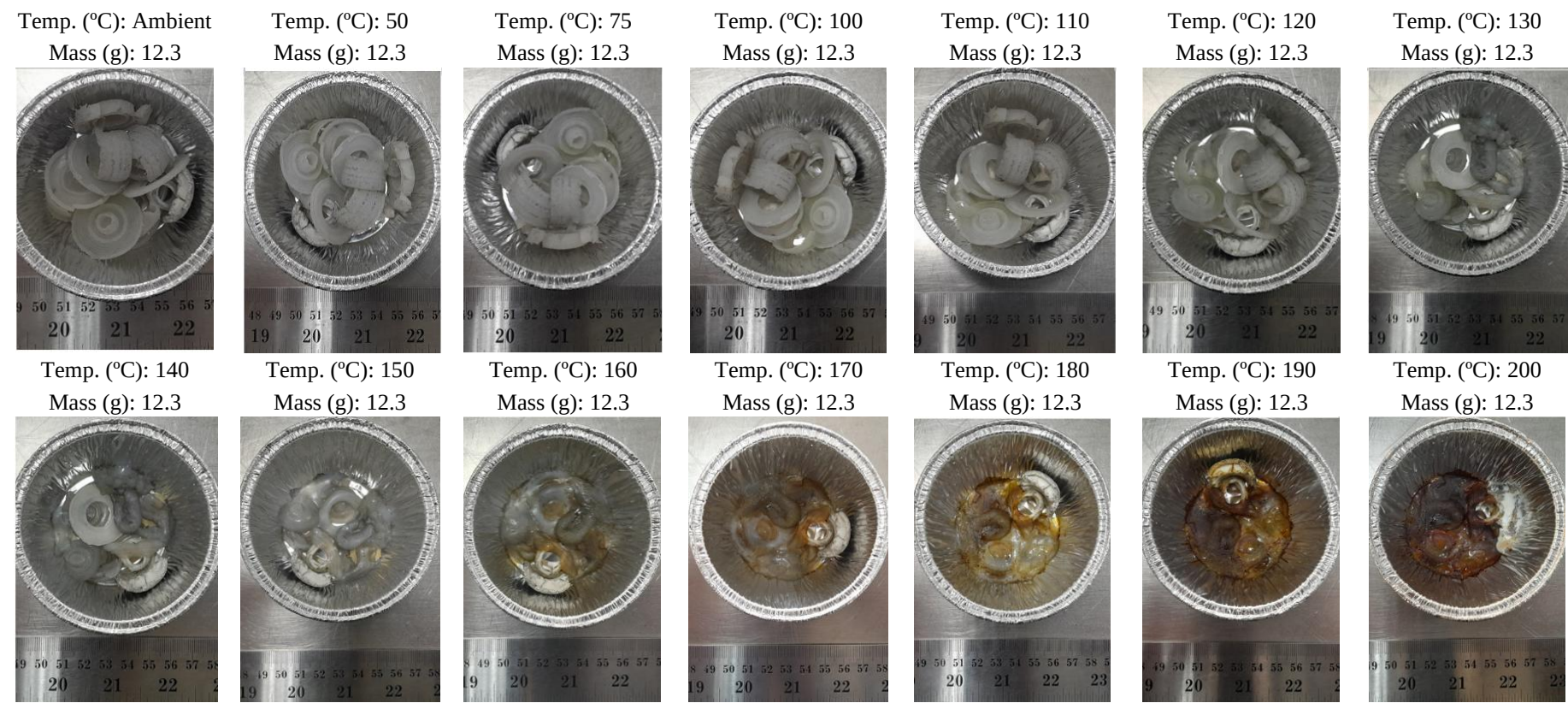


Figure A.4.10 - Sample B – Floating transparent plastics

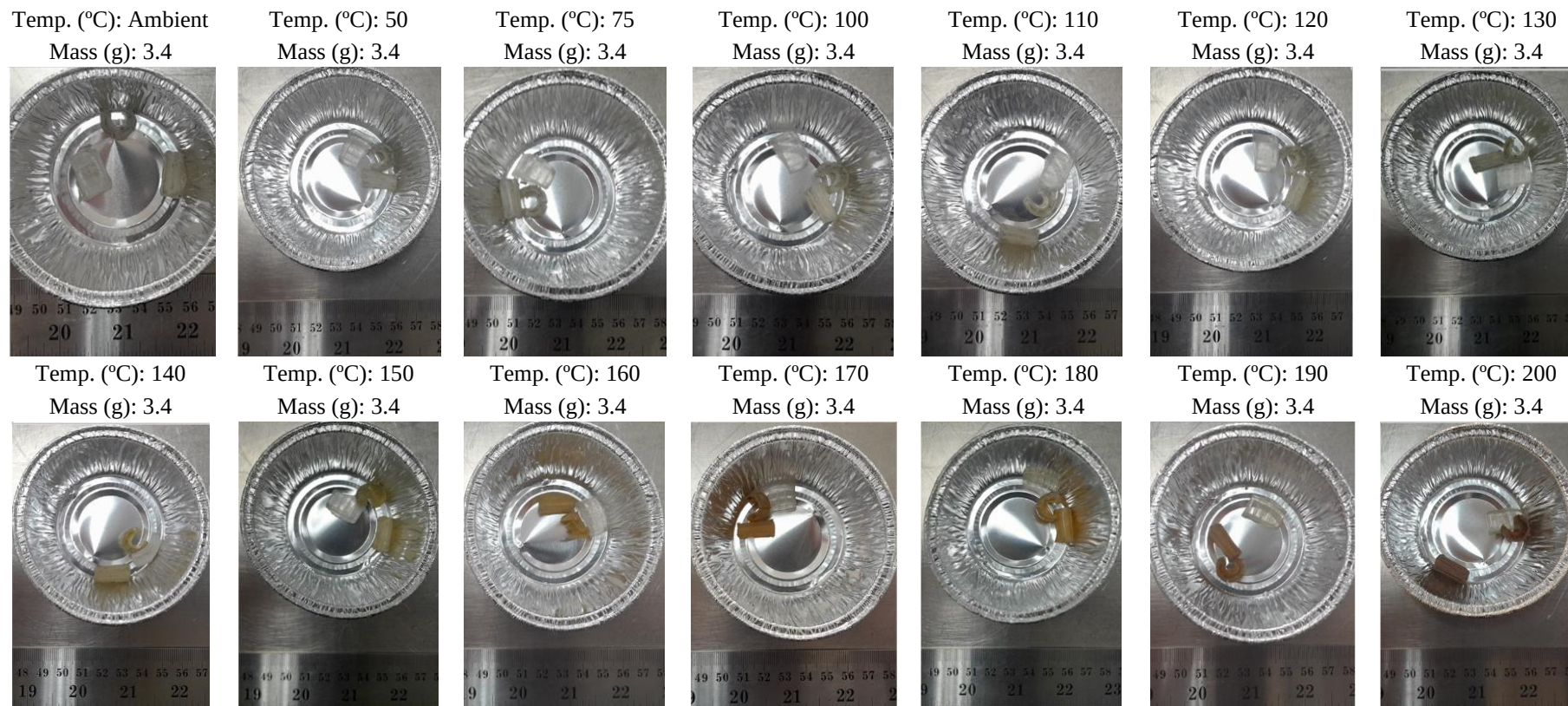


Figure A.4.11 - Sample B – Non floating transparent plastics

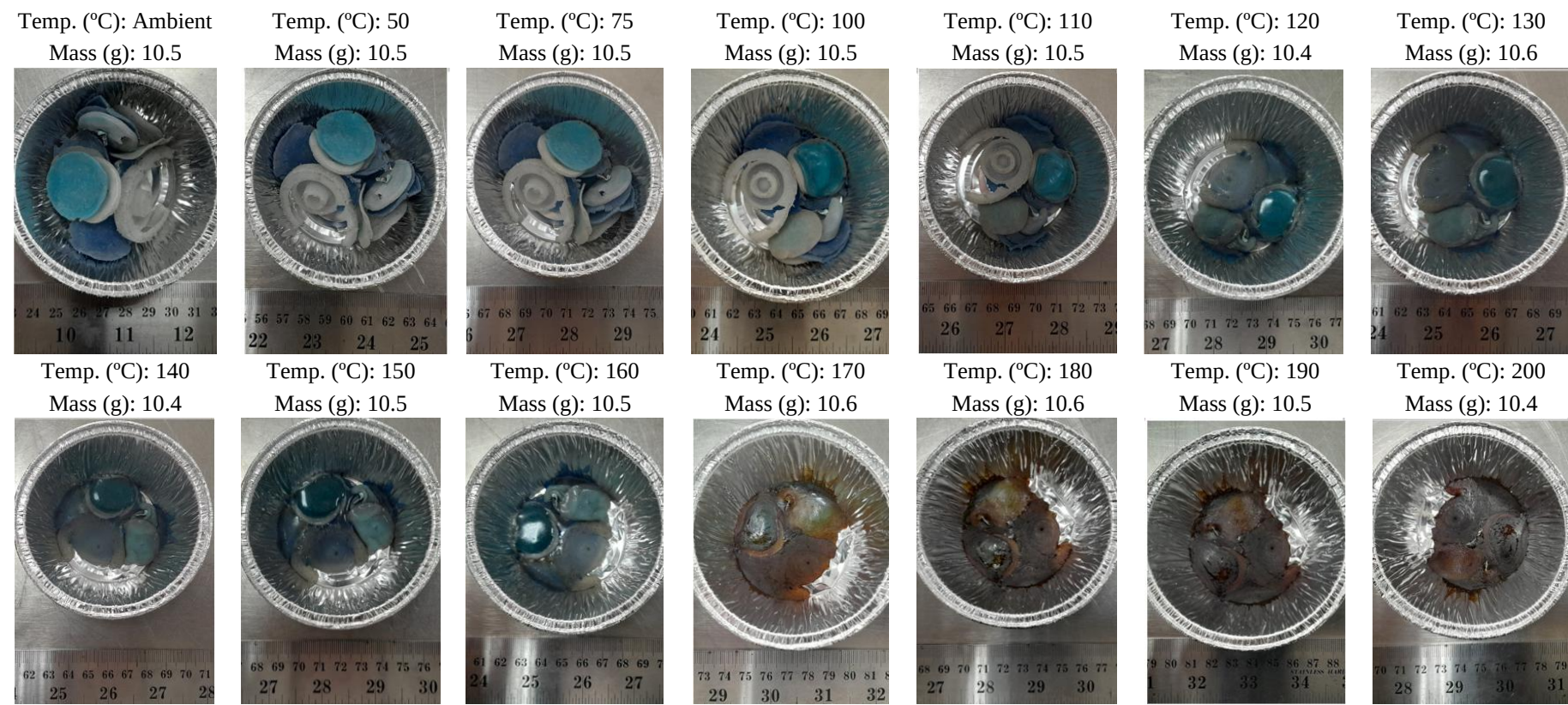


Figure A.4.12 - Sample B – Floating white capsules, floating blue capsules and floating transparent plastics

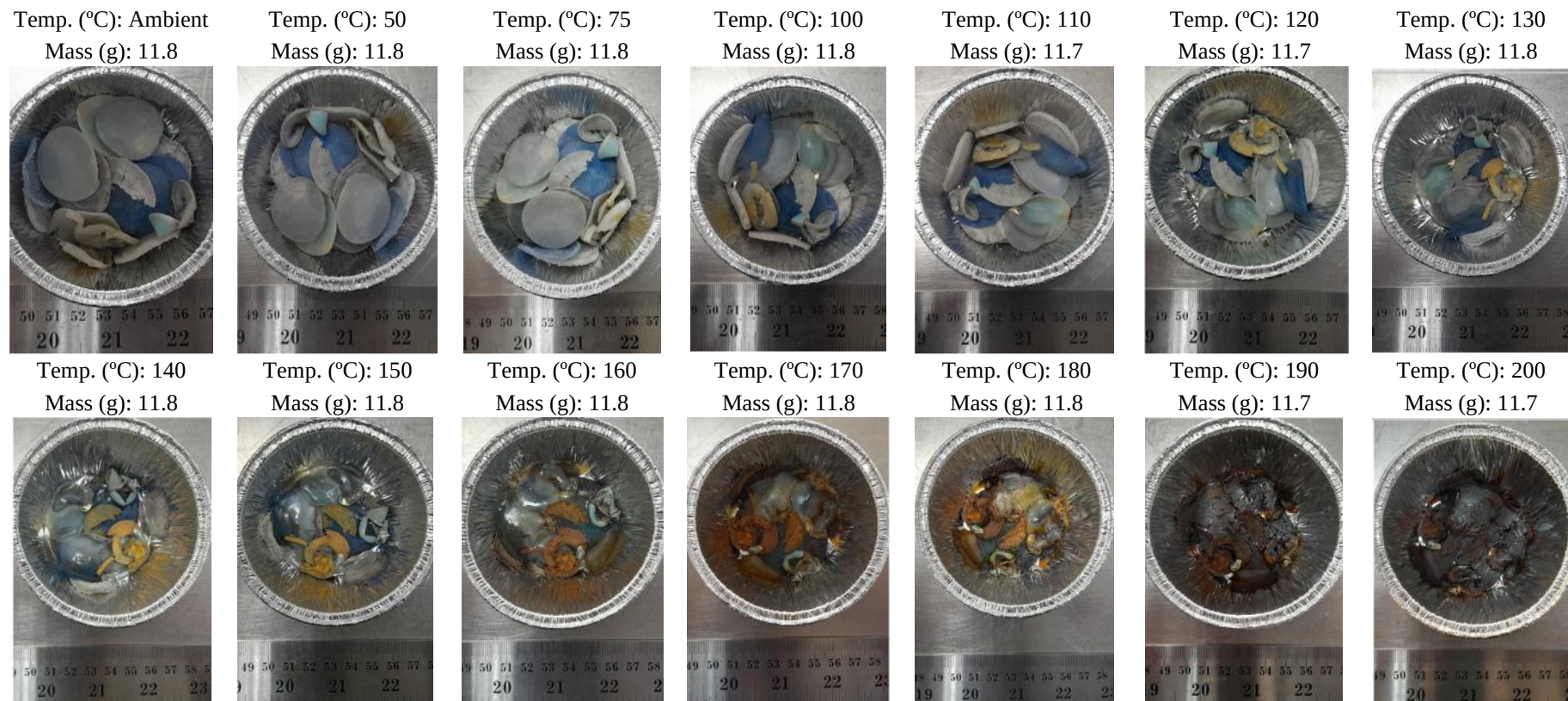


Figure A.4.13 - Sample B – Floating mixed paper capsules, floating blue capsules and floating white capsules

Annex 5: Melting point of sample C

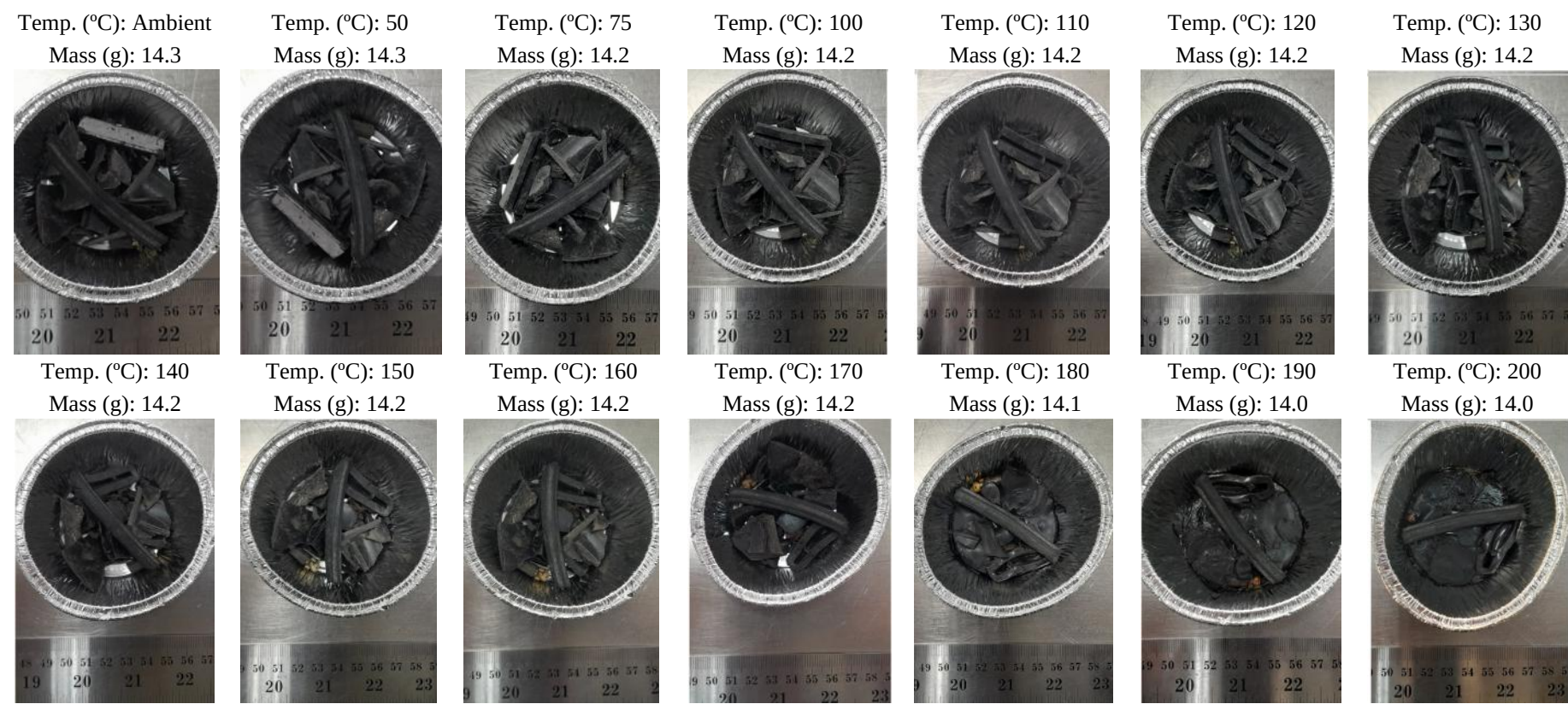


Figure A.5.1 - Sample C – Floating black plastic

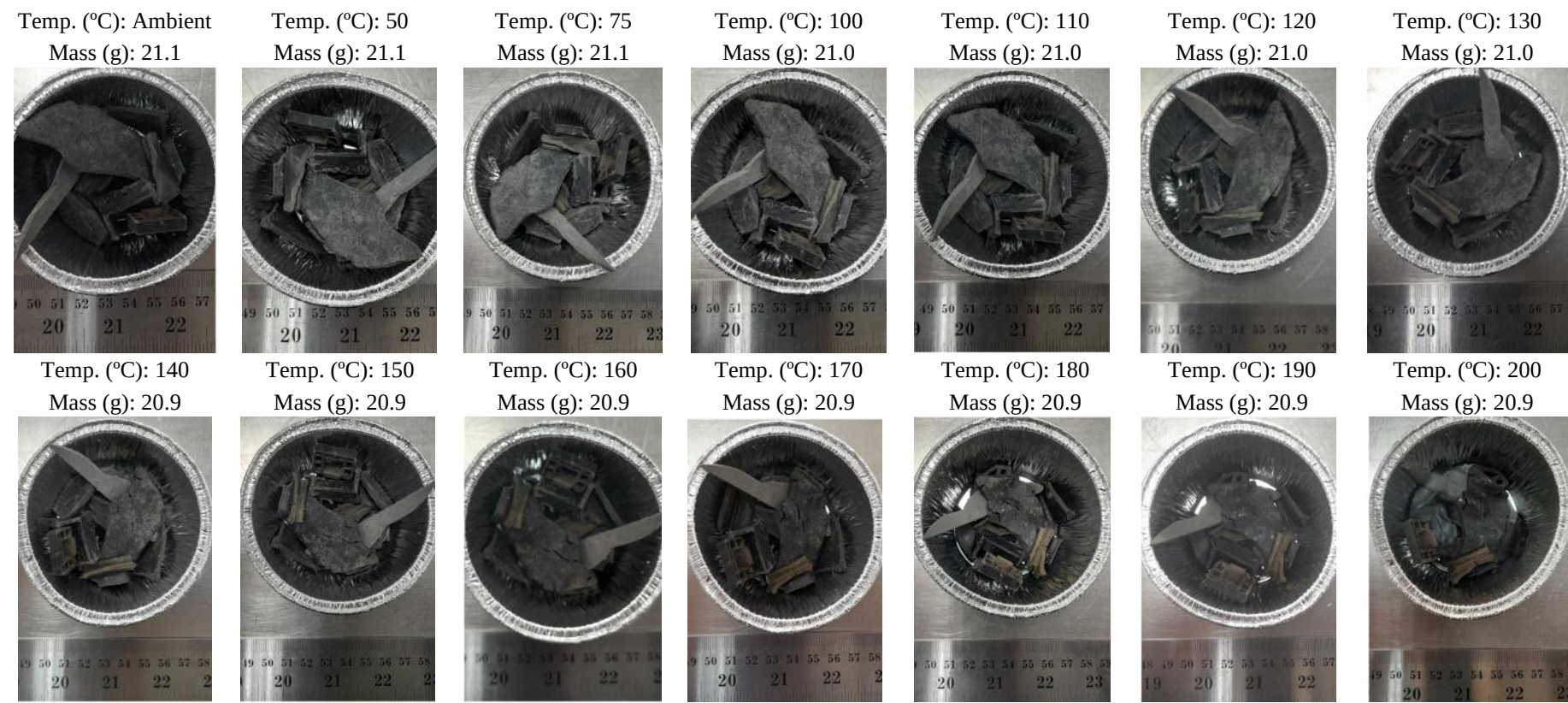


Figure A.5.2 - Sample C – Non floating black plastic



Figure A.5.3 - Sample C – Floating grey plastic

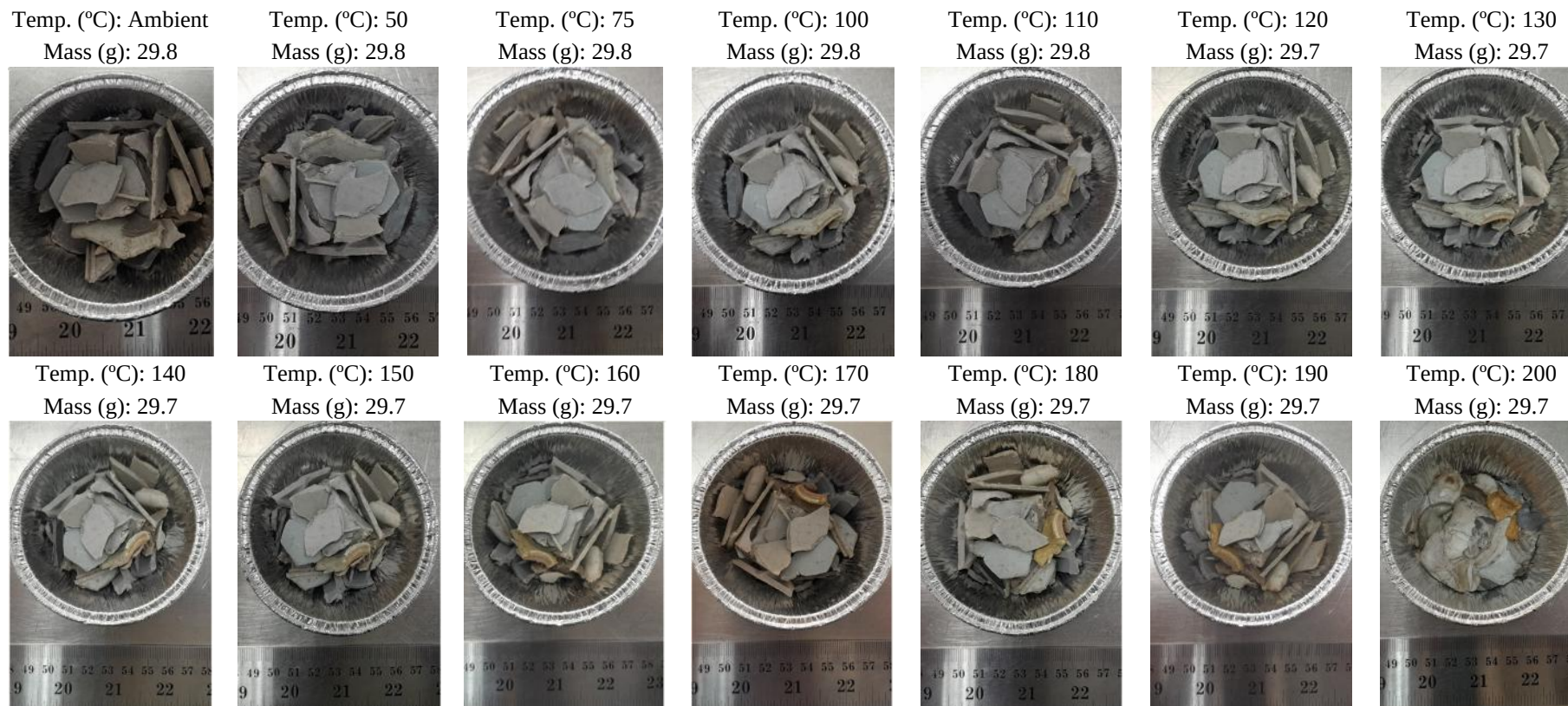


Figure A.5.4 - Sample C – Non floating grey plastic

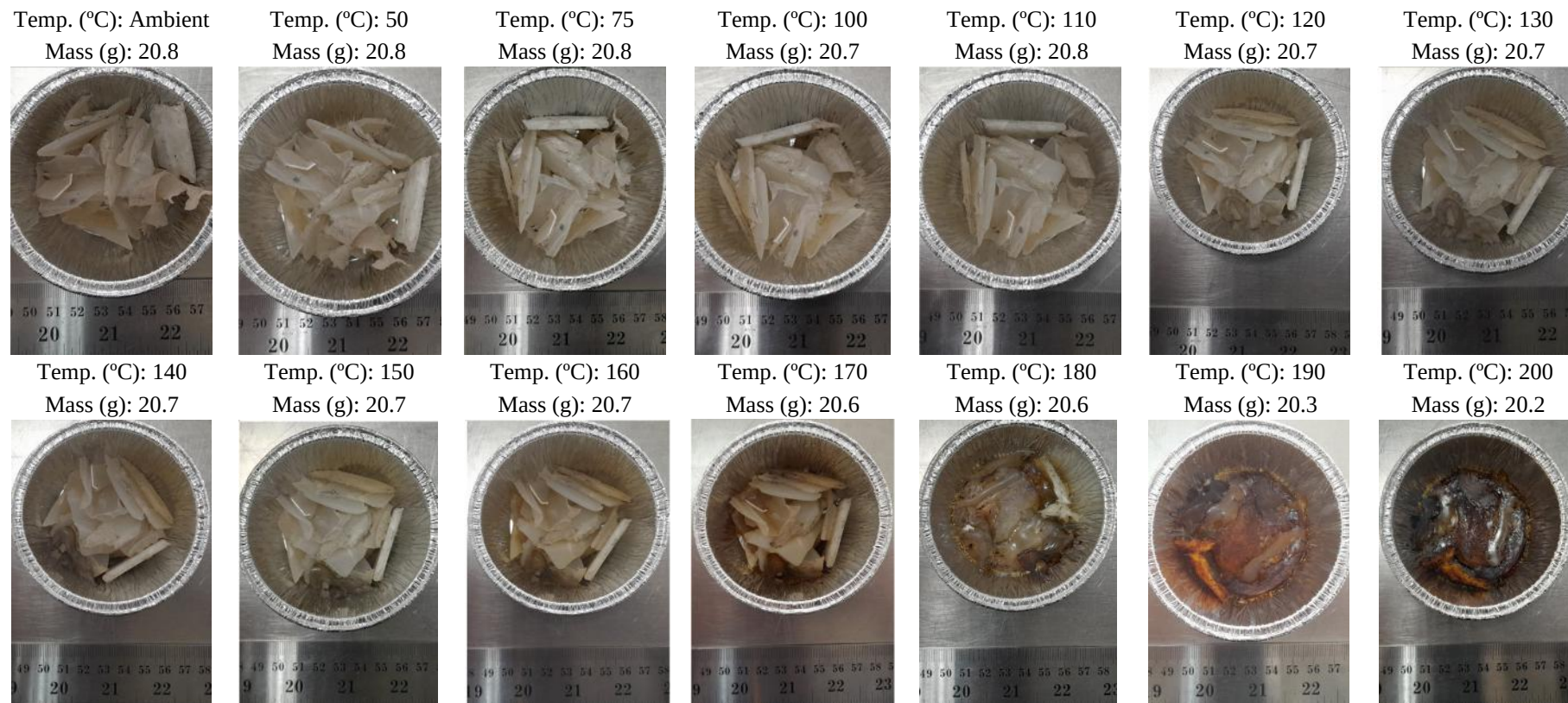


Figure A.5.5 - Sample C – Floating transparent plastic

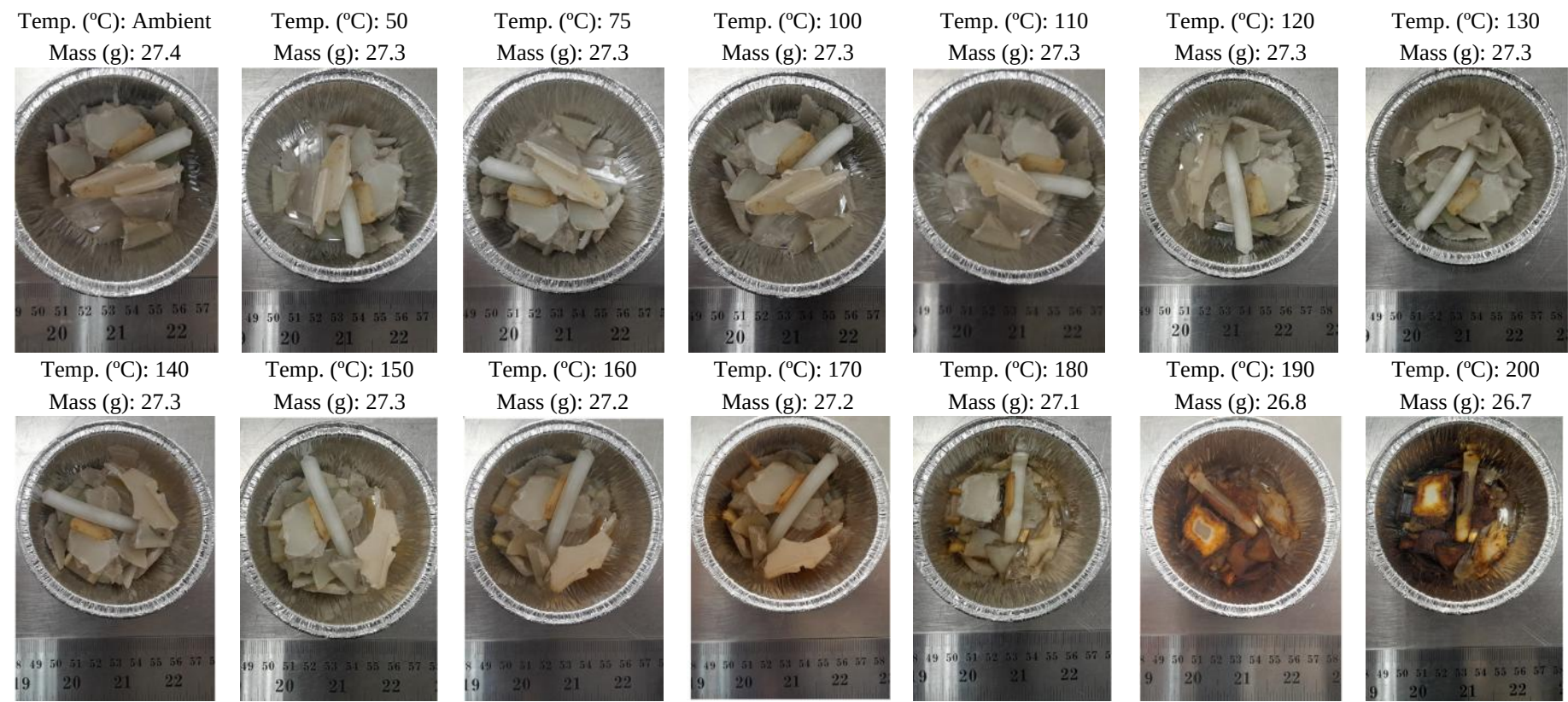


Figure A.5.6 - Sample C – Non floating transparent plastic

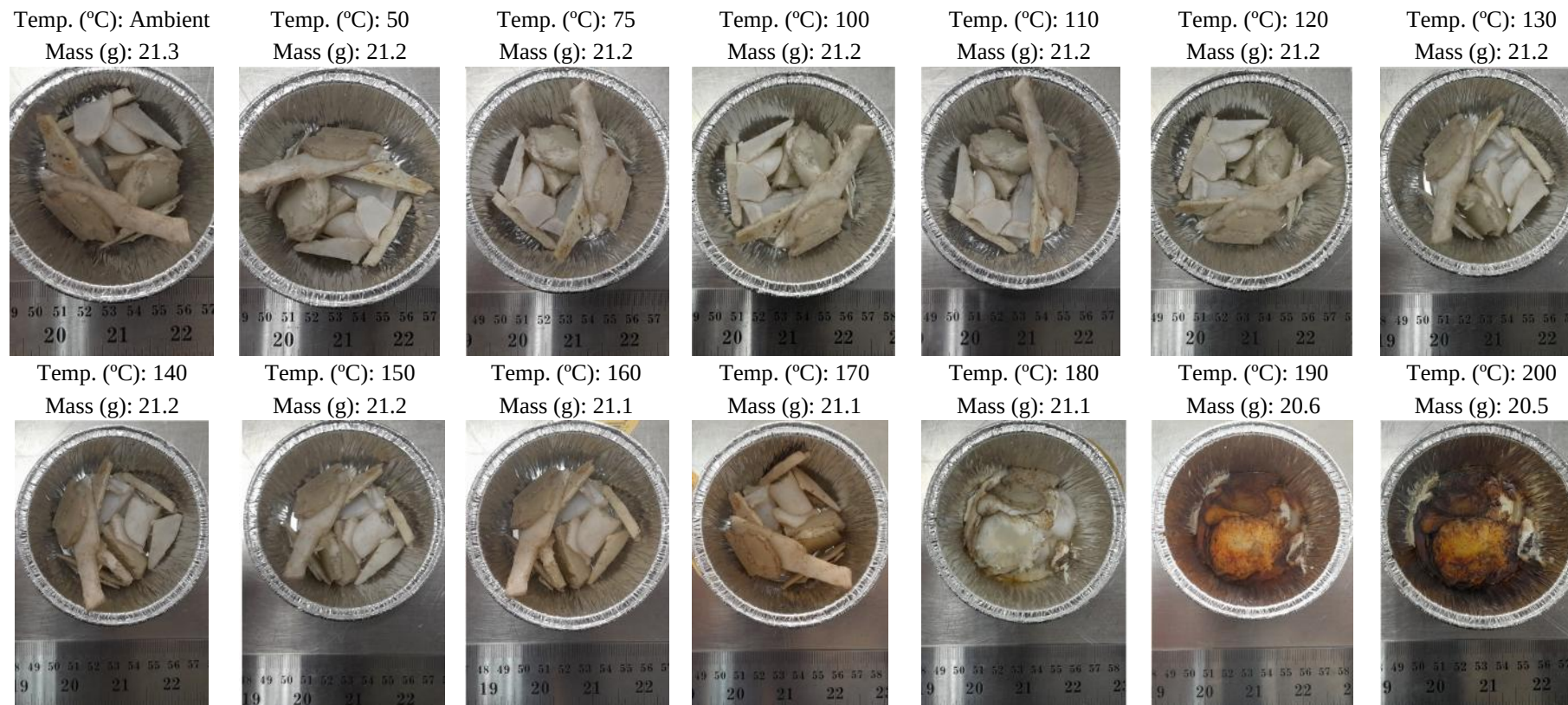


Figure A.5.7 - Sample C – Floating white plastics

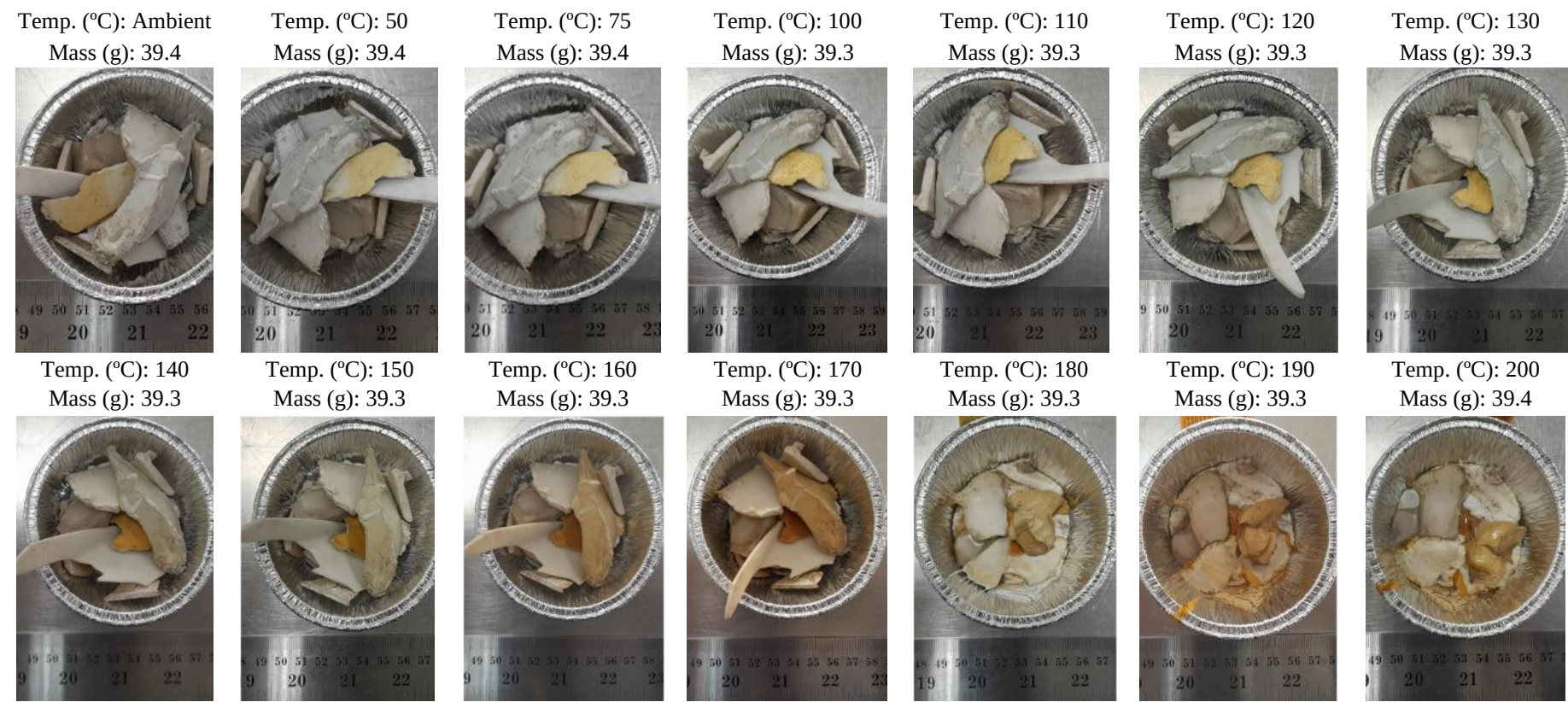


Figure A.5.8 - Sample C – Non floating white plastics

Annex 6: Melting point of sample D

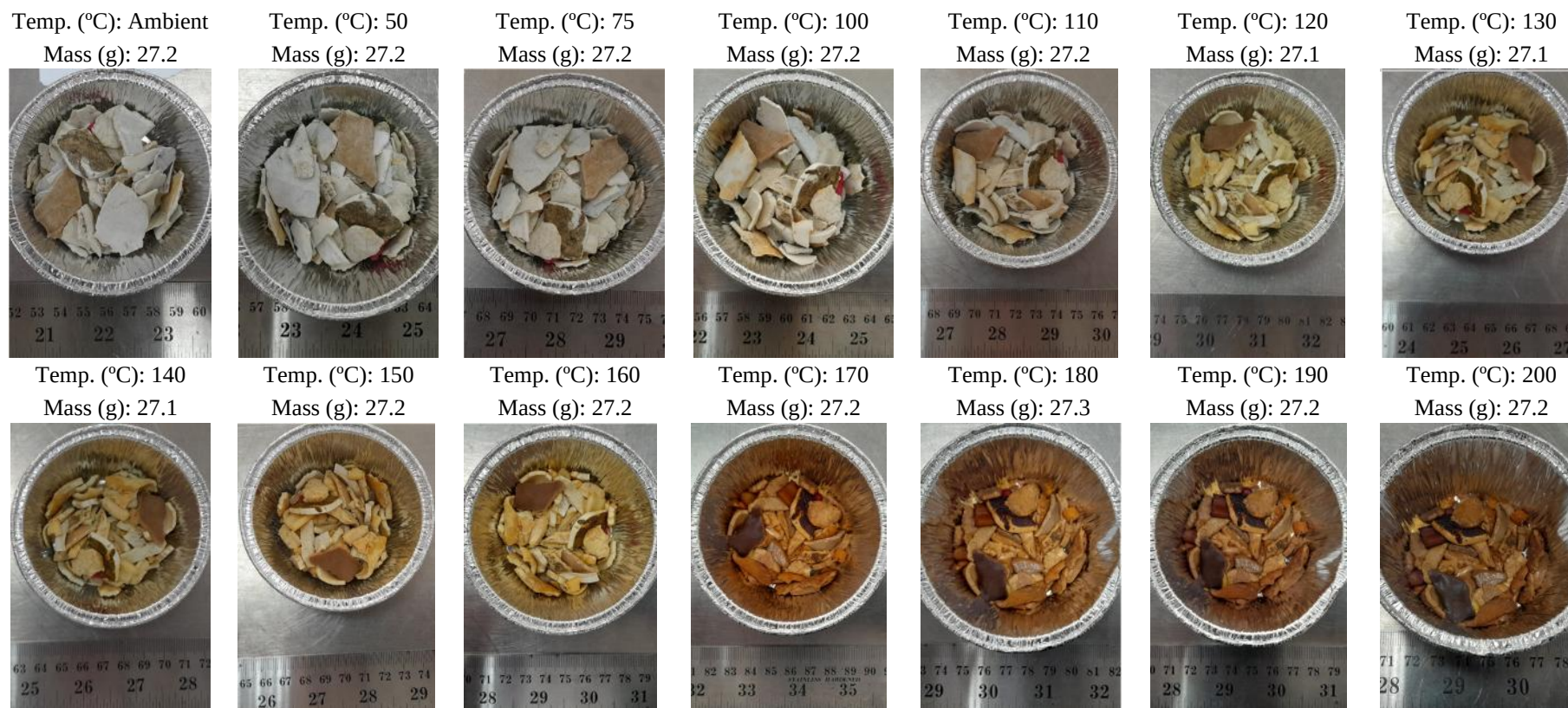


Figure A.6.1 - Sample D – PS/ABS Refrigerators (PS2)

Annex 7: Melting point of sample E

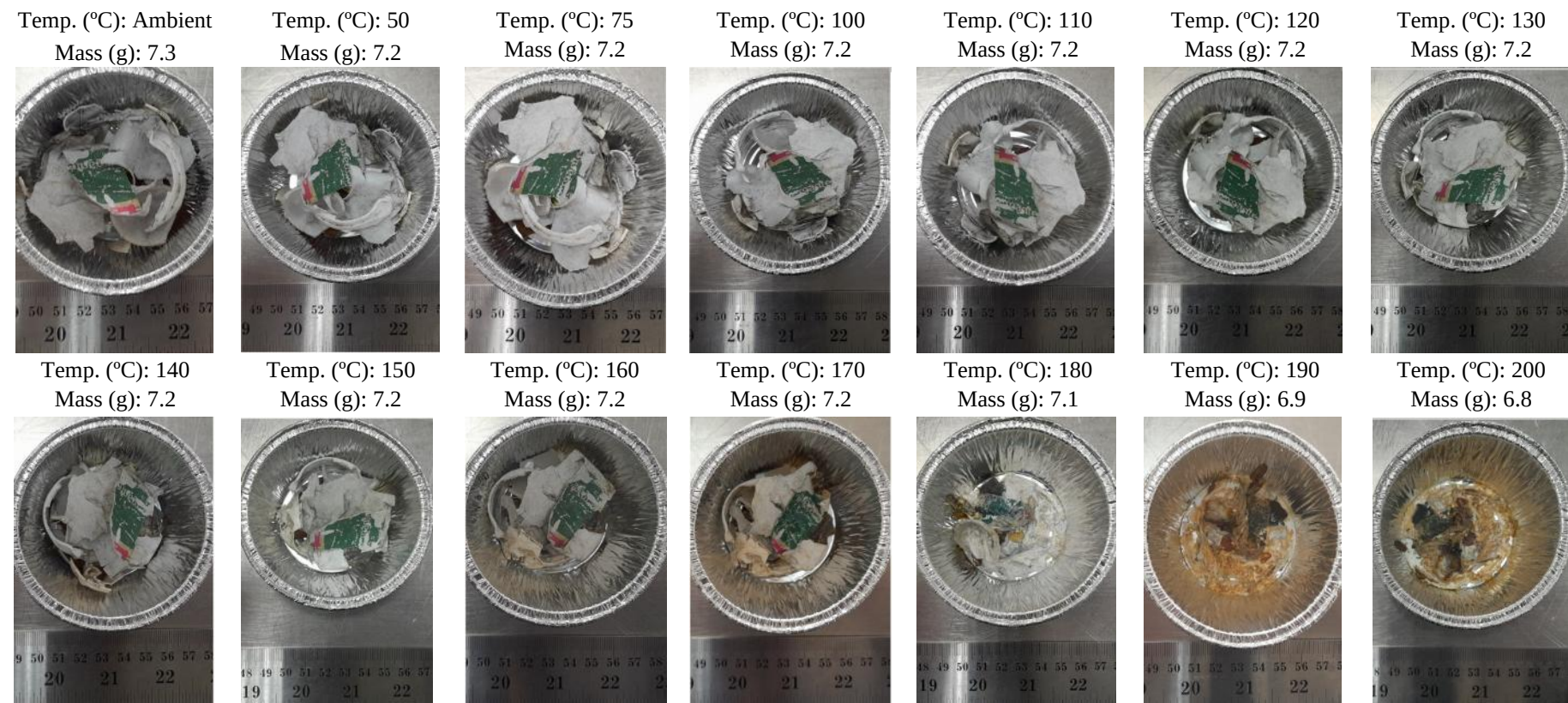


Figure A.7.1 - Sample E – Floating flexible white plastic

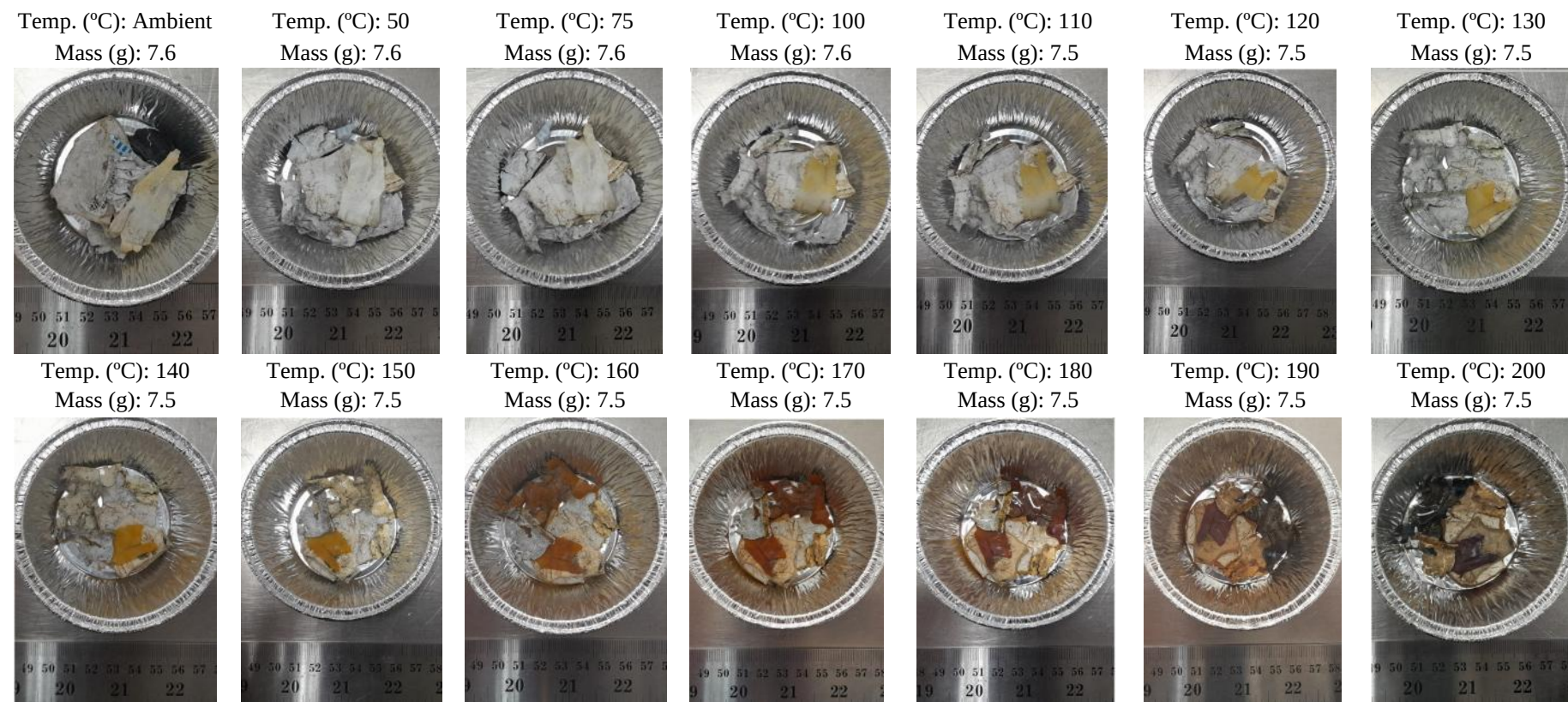


Figure A.7.2 - Sample E – Non floating flexible white plastic

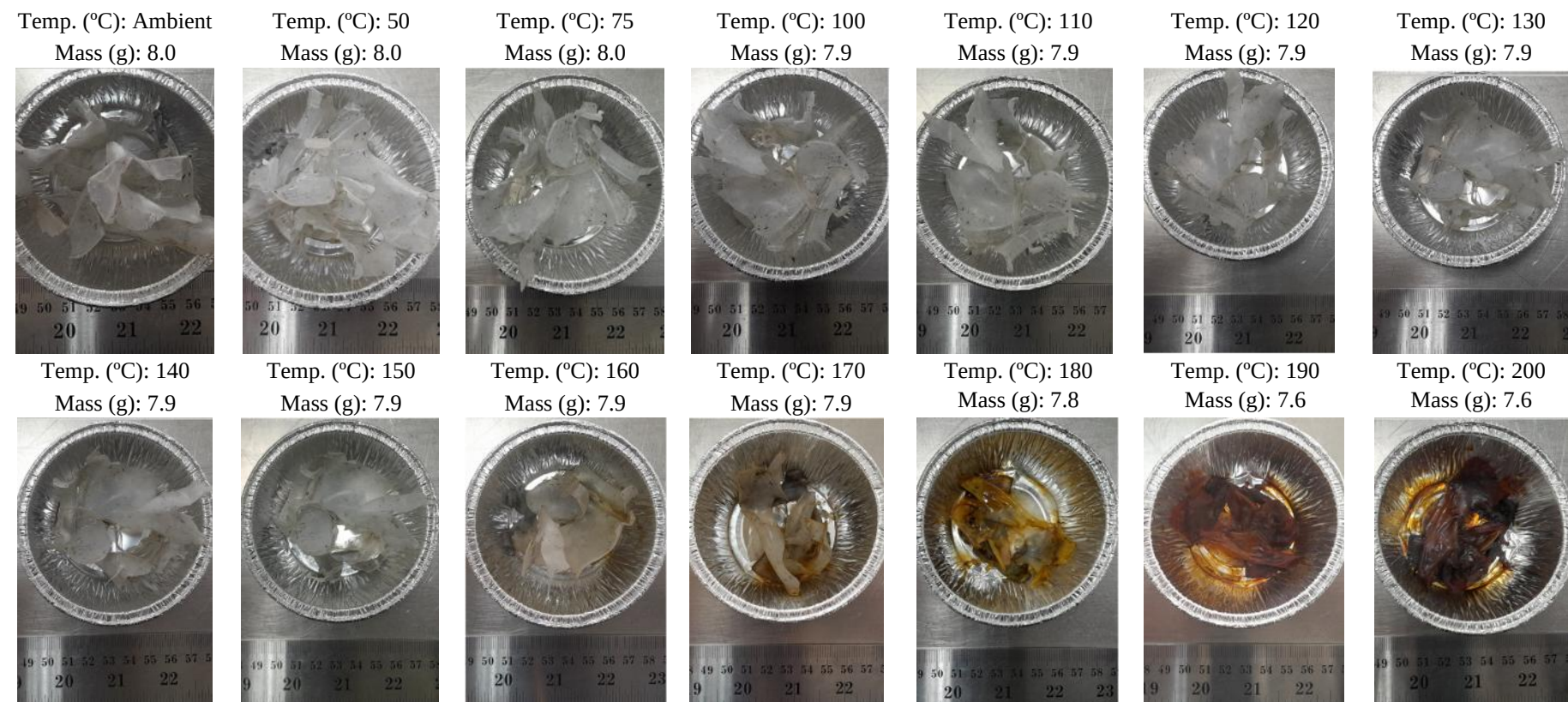


Figure A.7.3 - Sampe E – Floating flexible transparent plastics

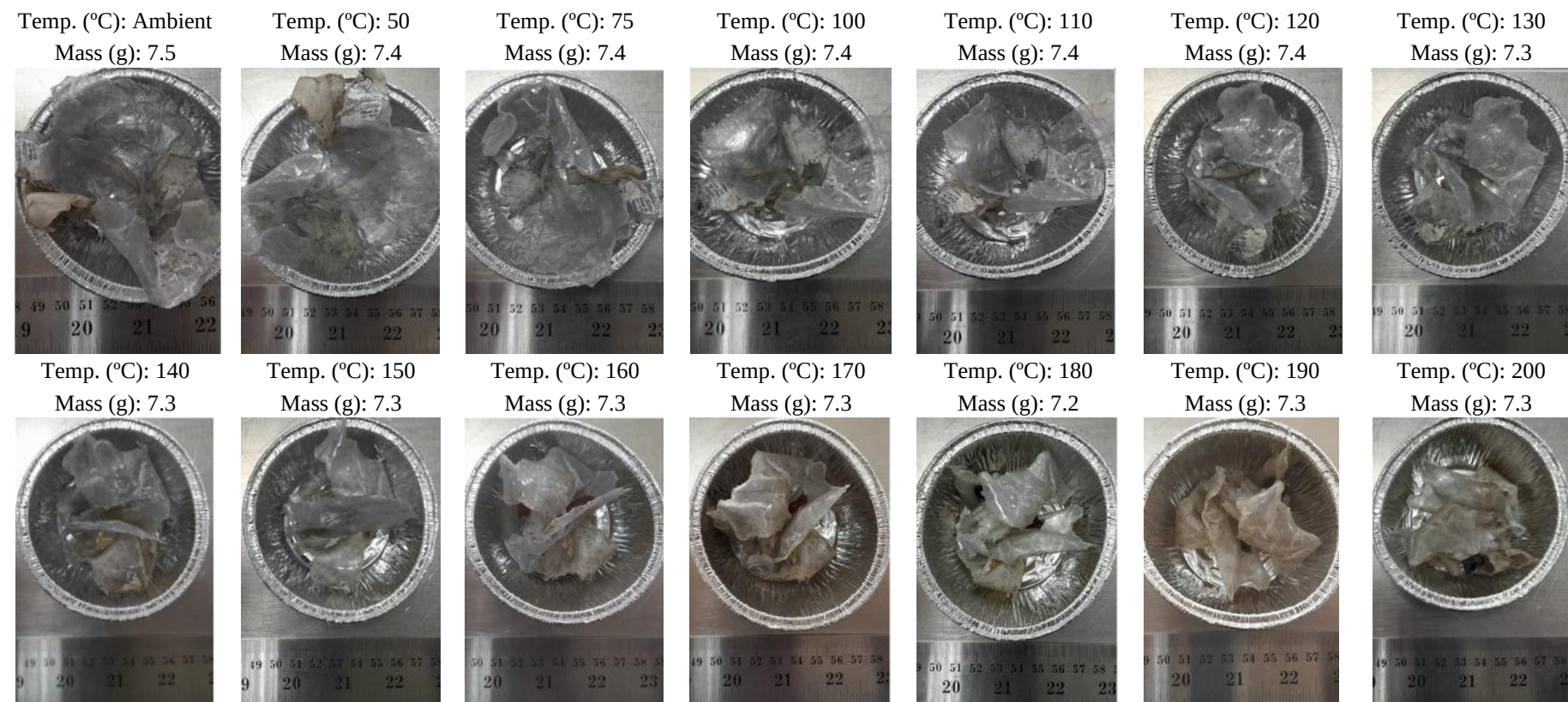


Figure A.7.4 - Sample E – Non floating flexible transparent plastics

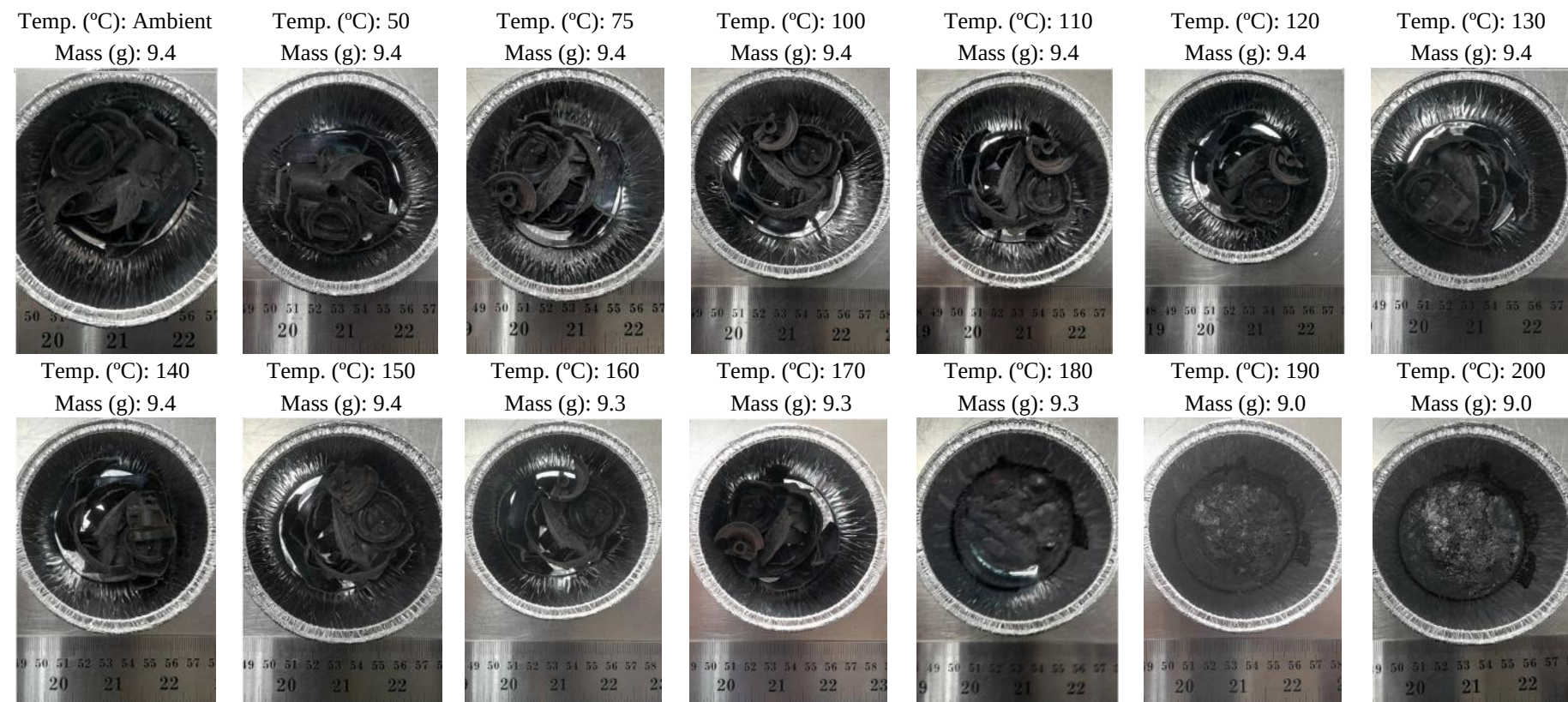


Figure A.7.5 - Sample E – Floating flexible black plastics

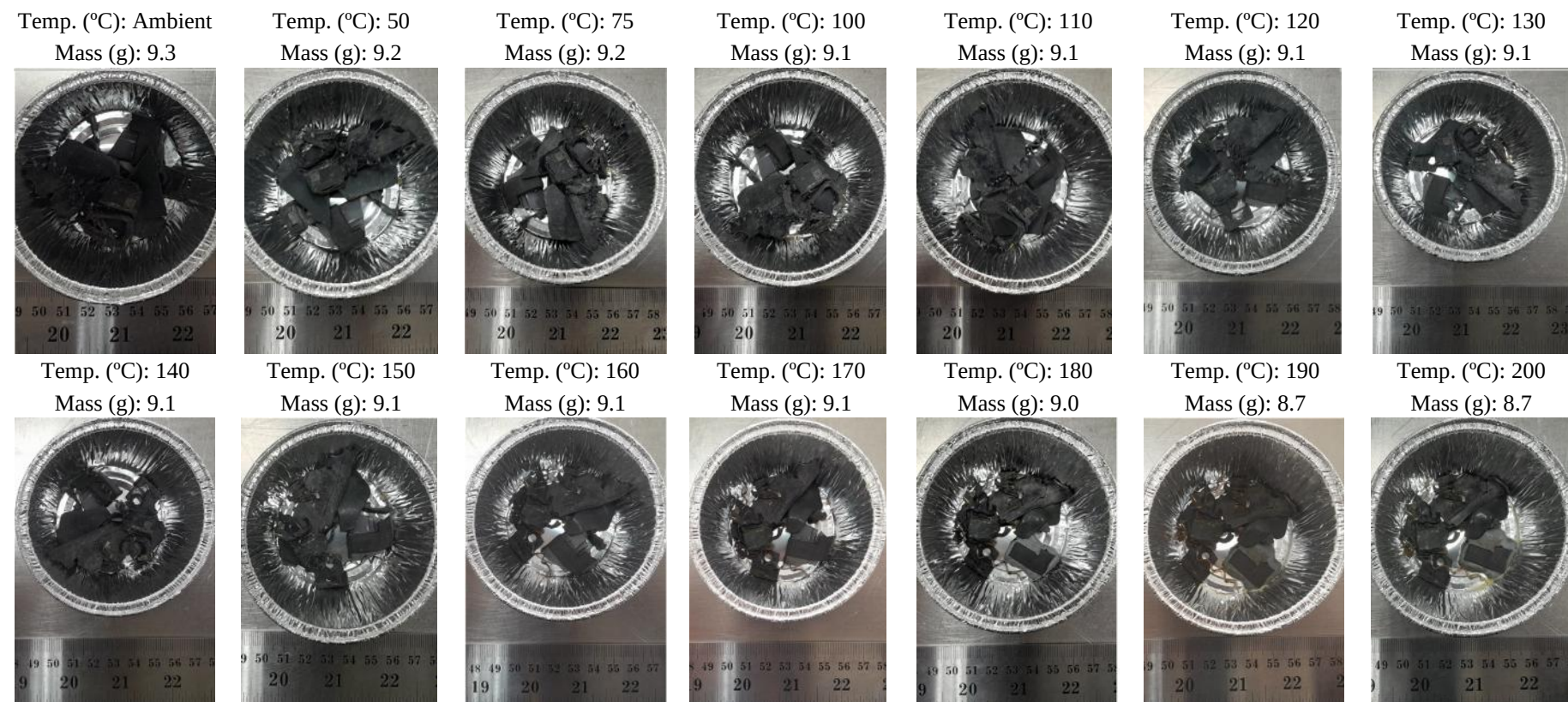


Figure A.7.6 - Sample E – Non floating flexible black plastics

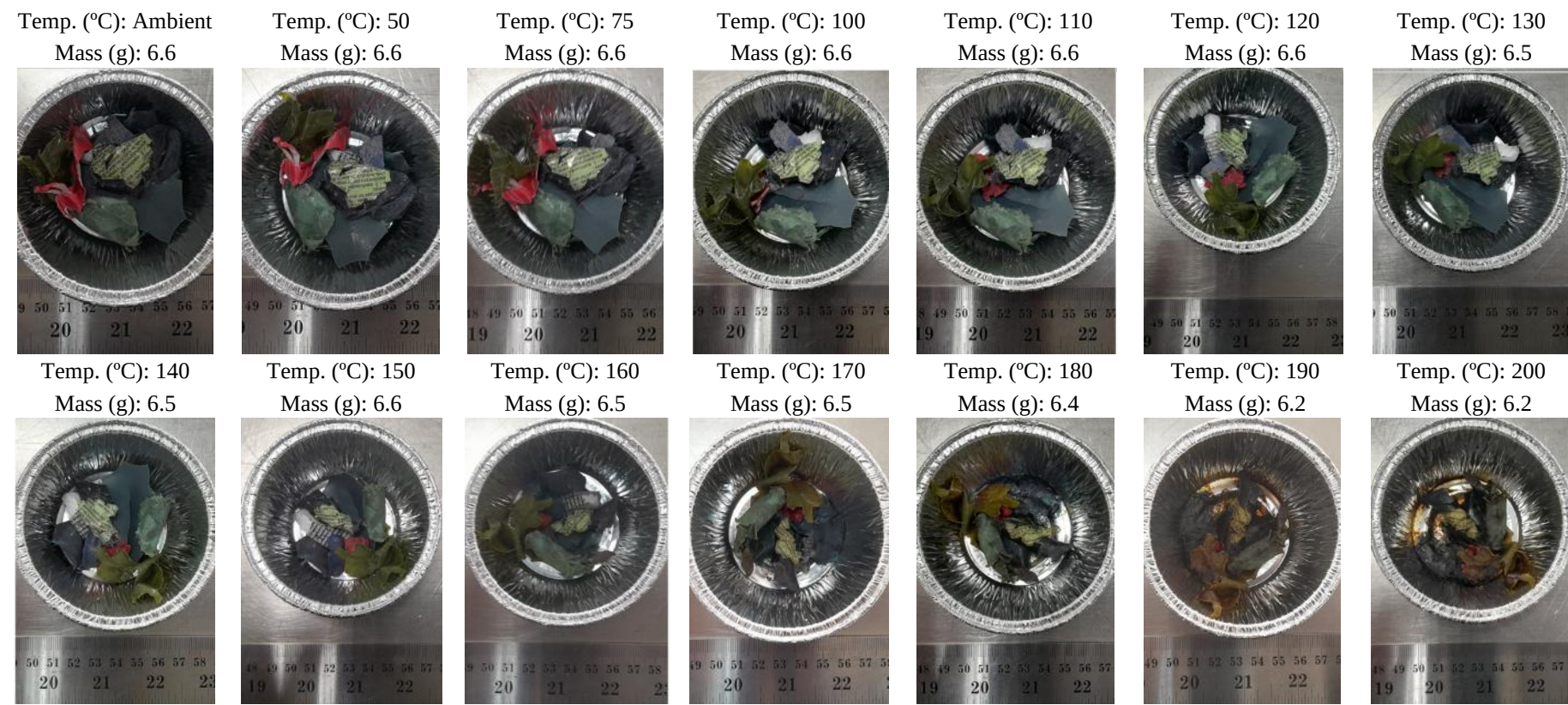


Figure A.7.7 - Sample E – Floating mixed flexible plastics

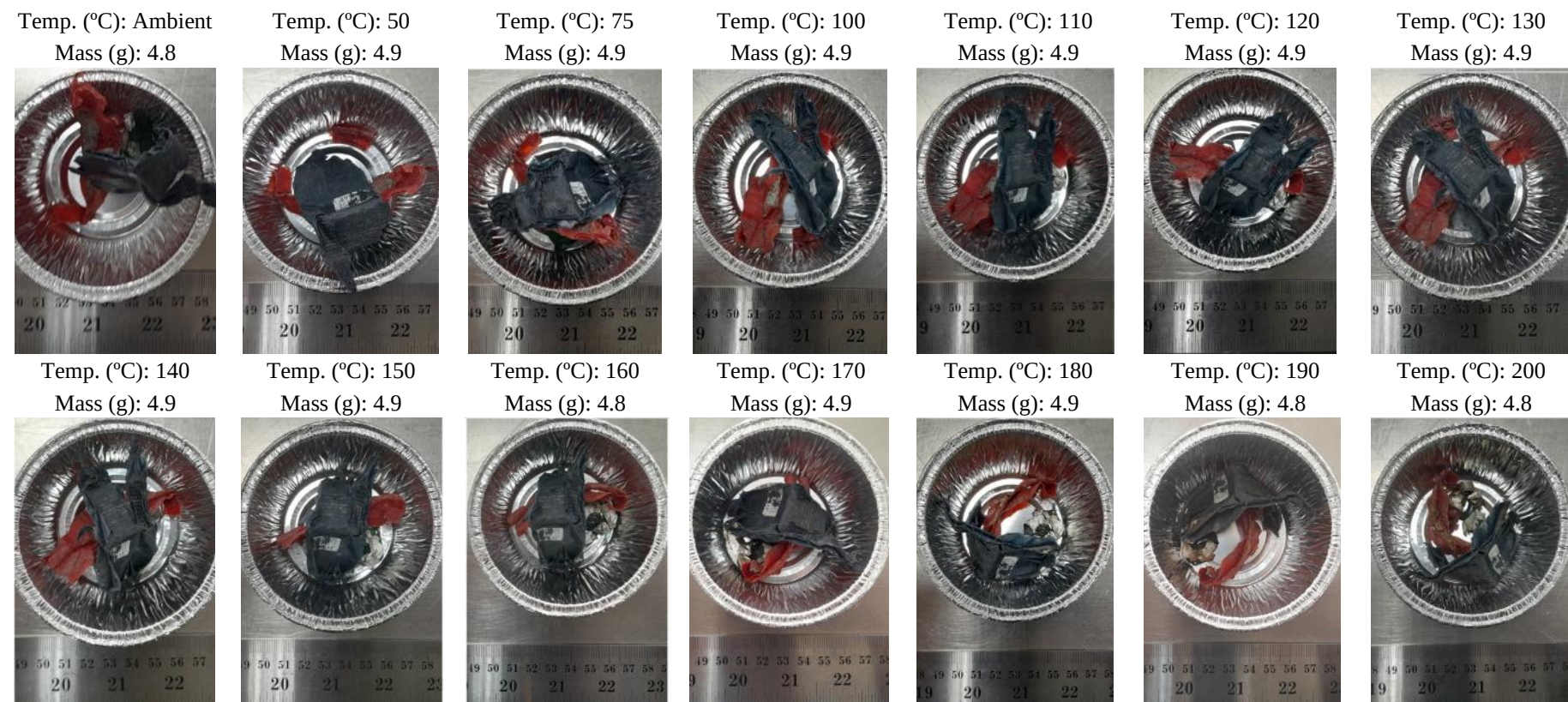


Figure A.7.8 - Sample E – Non floating mixed flexible plastics

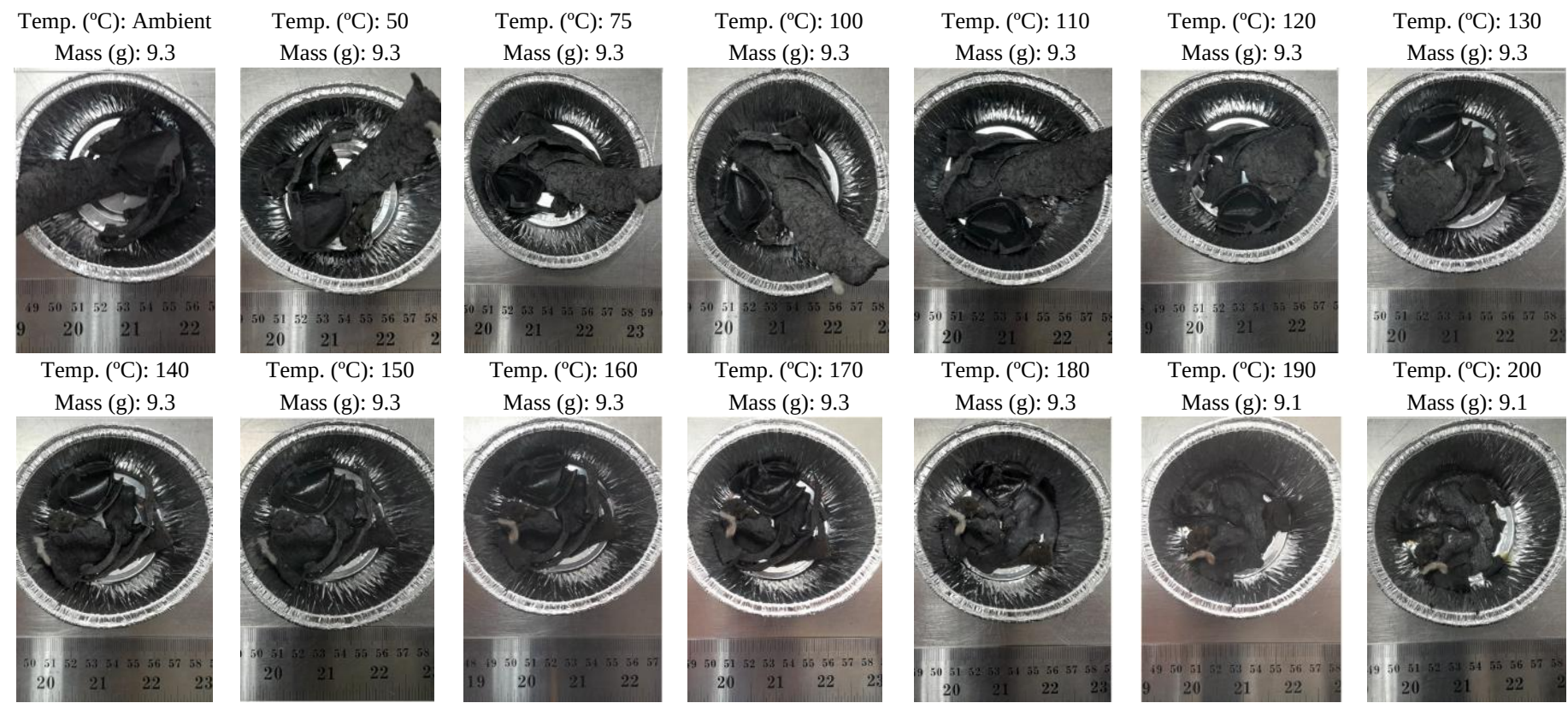


Figure A.7.9 - Sample E – Floating rubber

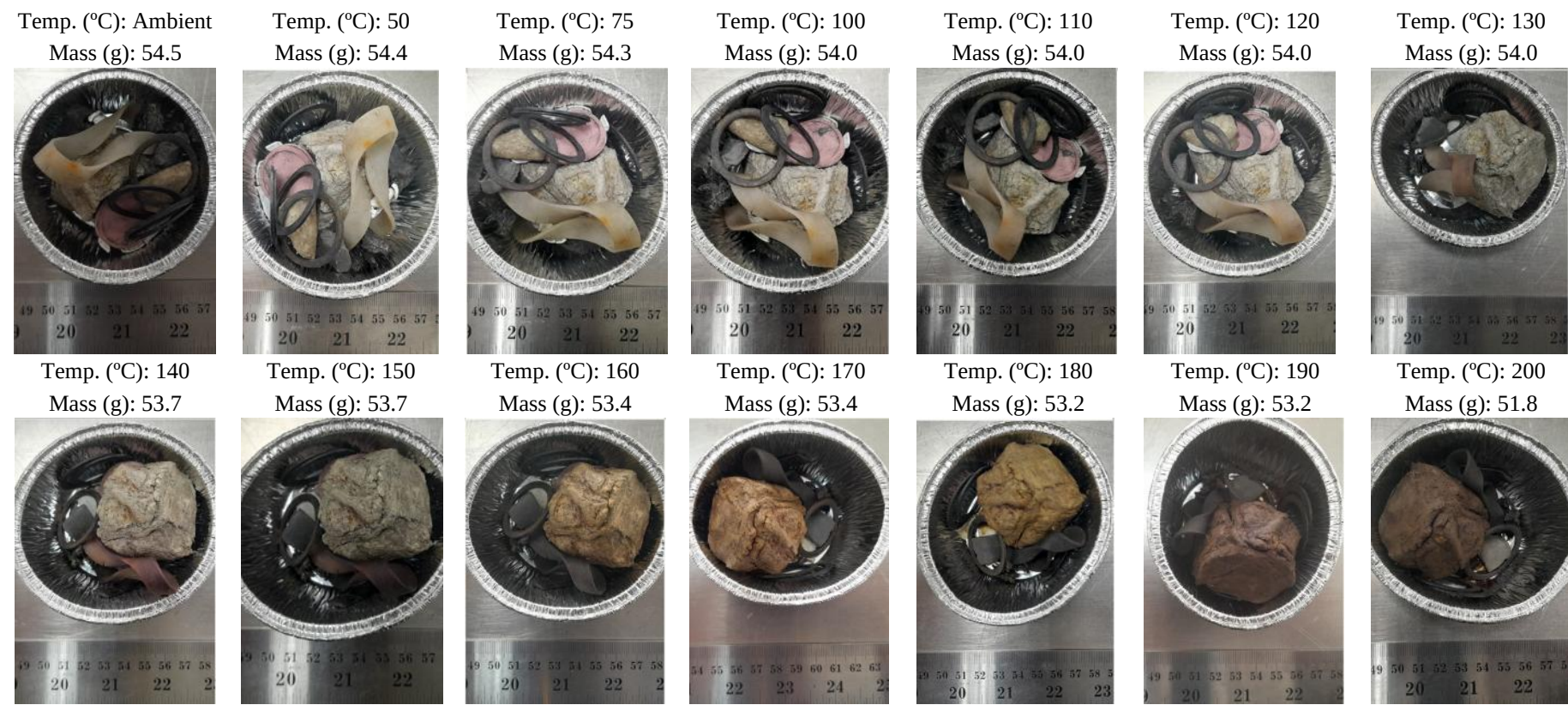


Figure A.7.10 - Sample E – Non floating rubber

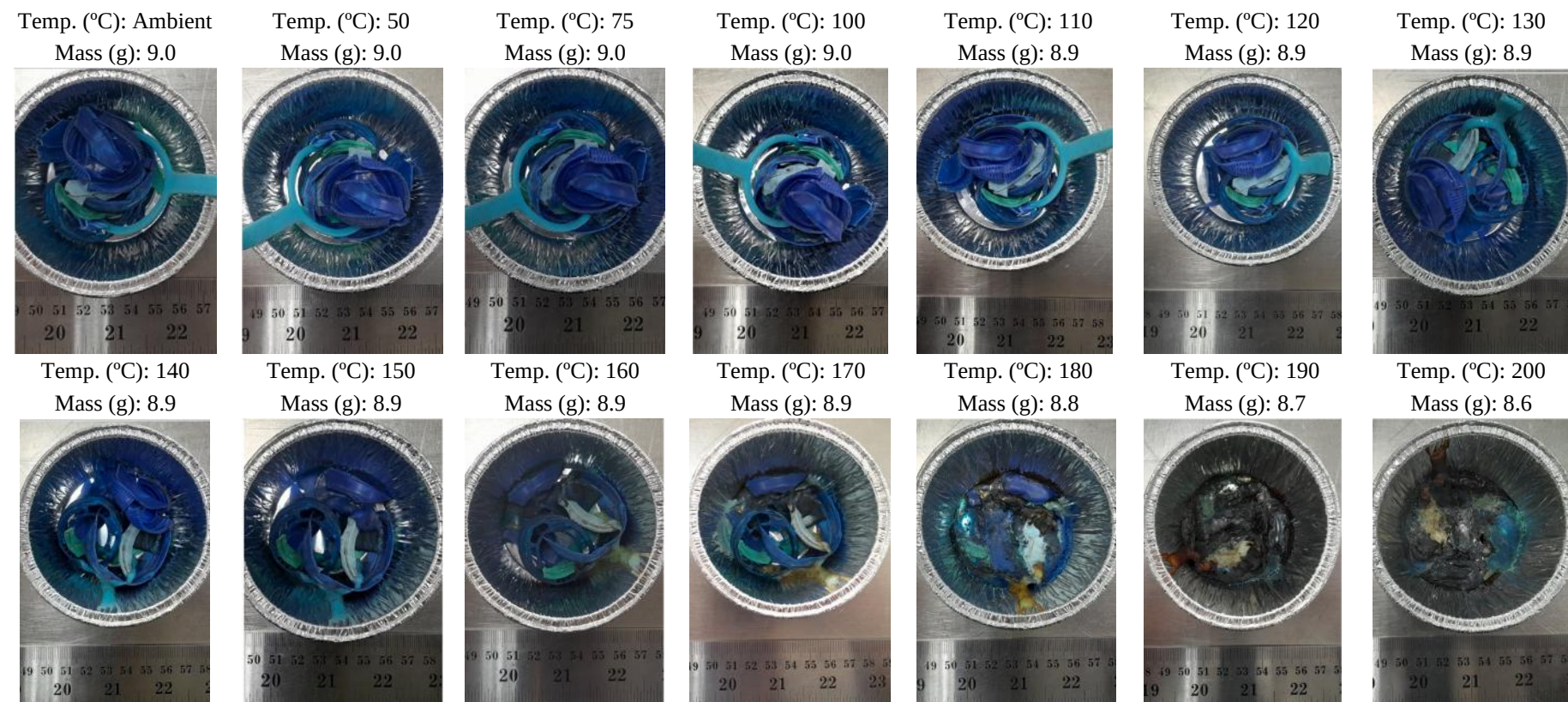


Figure A.7.11 - Sample E – Floating rigid blue plastics

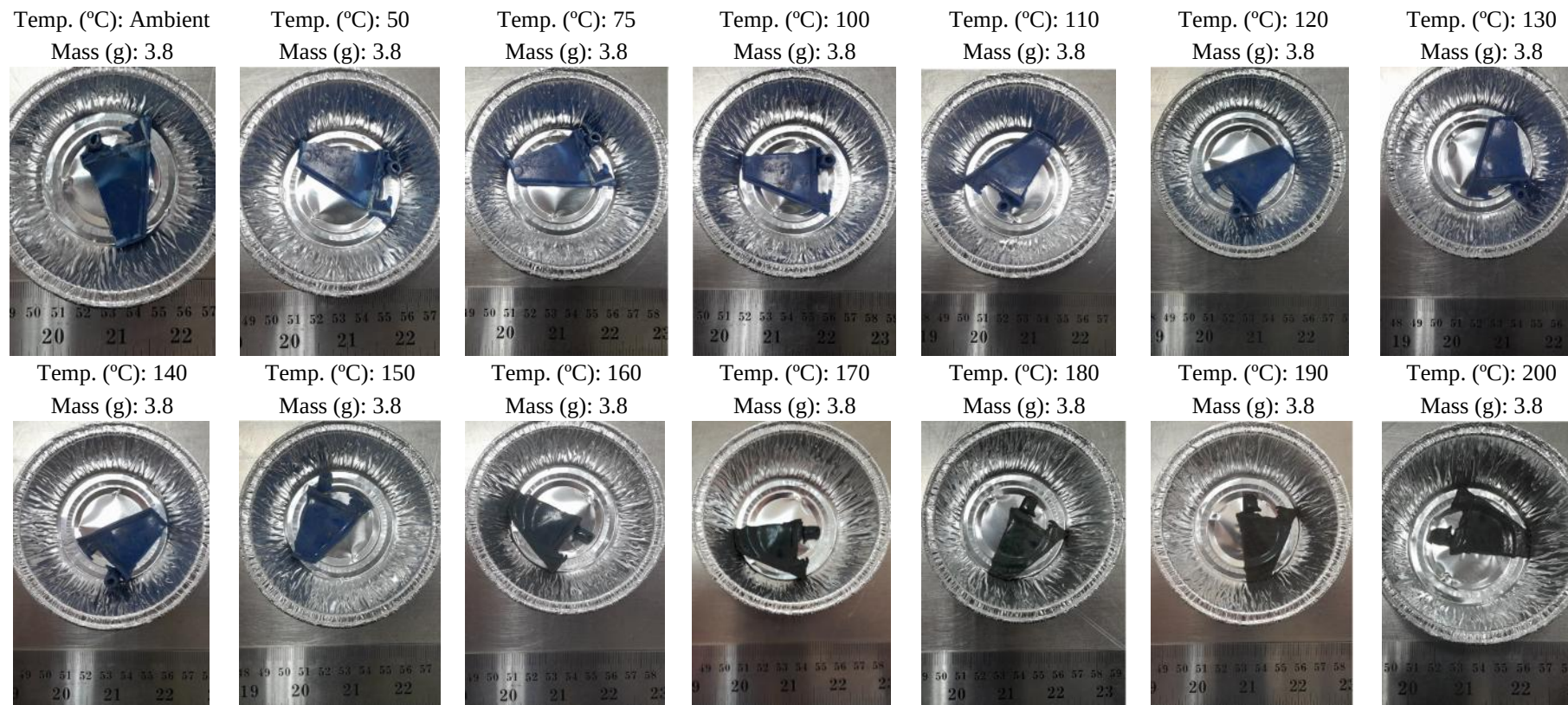


Figure A.7.12 - Sample E – Non floating rigid blue plastics

Annex 8: Melting point of sample F

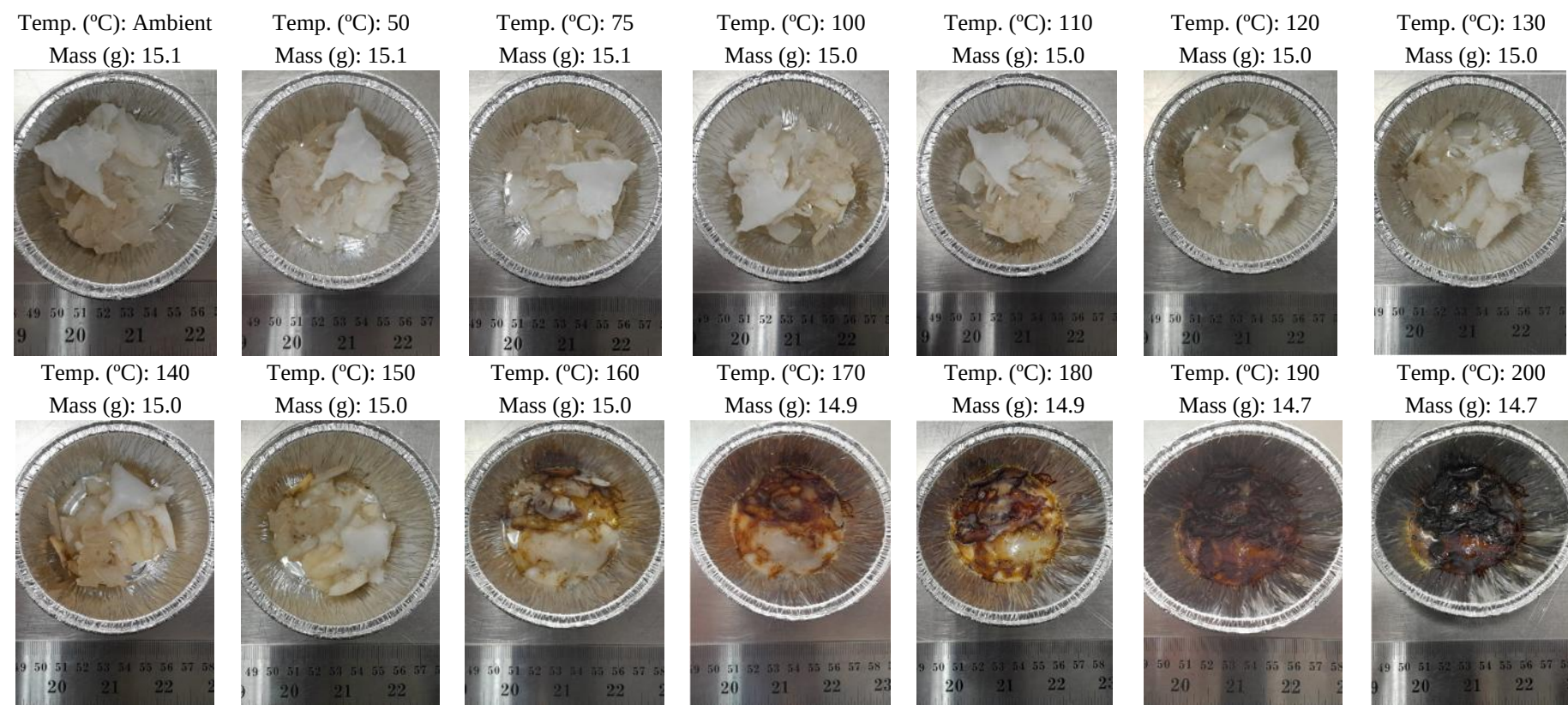


Figure A.8.1 - Sample F – Floating rigid transparent plastics

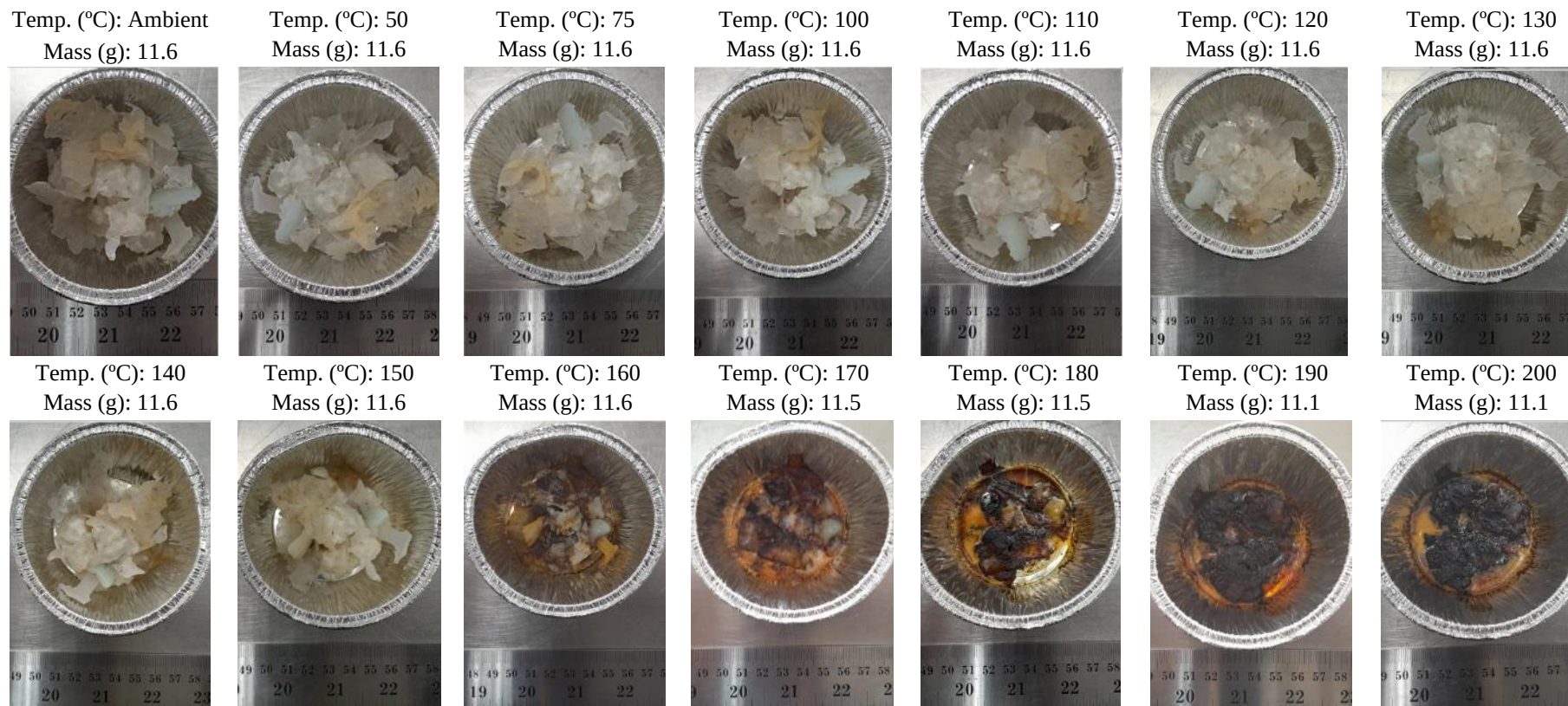


Figure A.8.2 - Sample F – Floating flexible transparent plastics

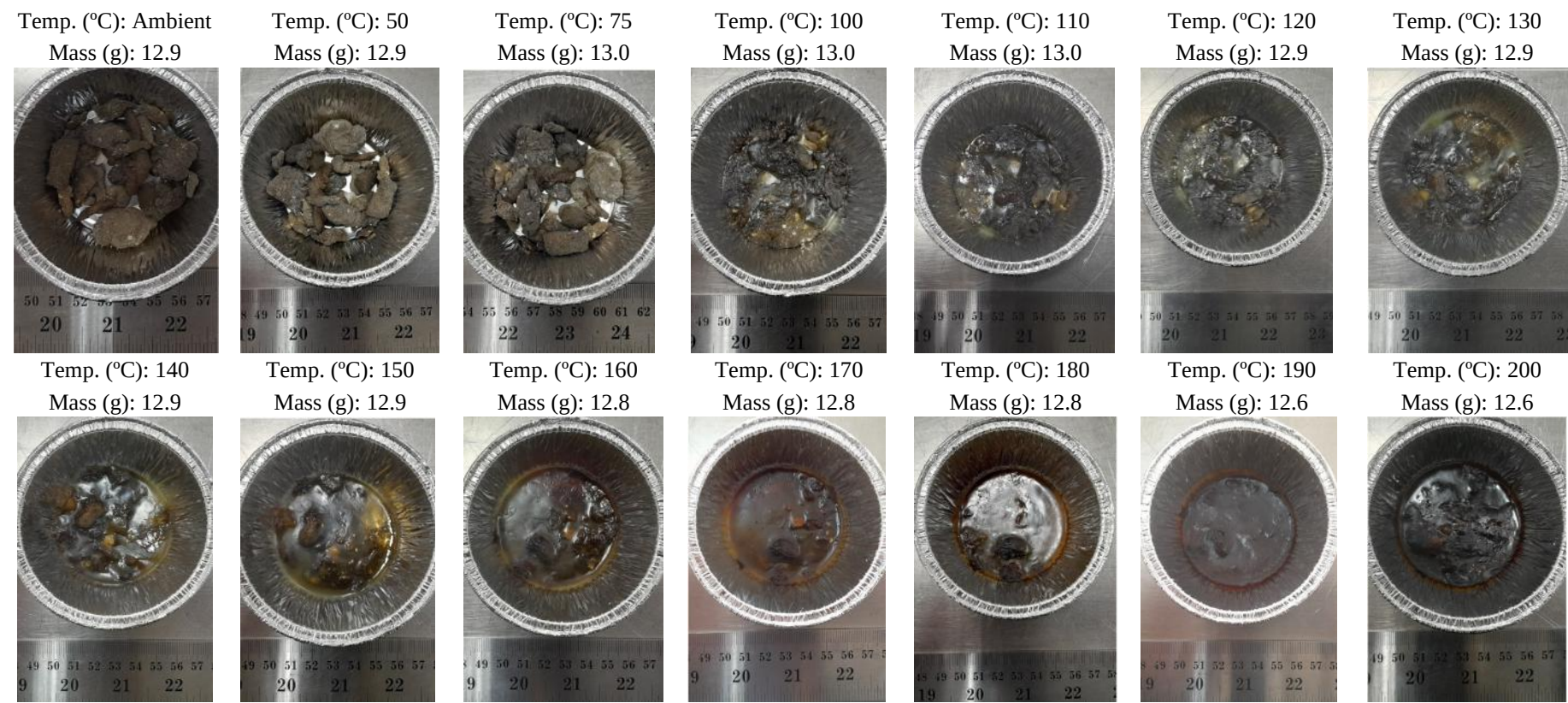


Figure A.8.3 - Sample F – Floating silicone

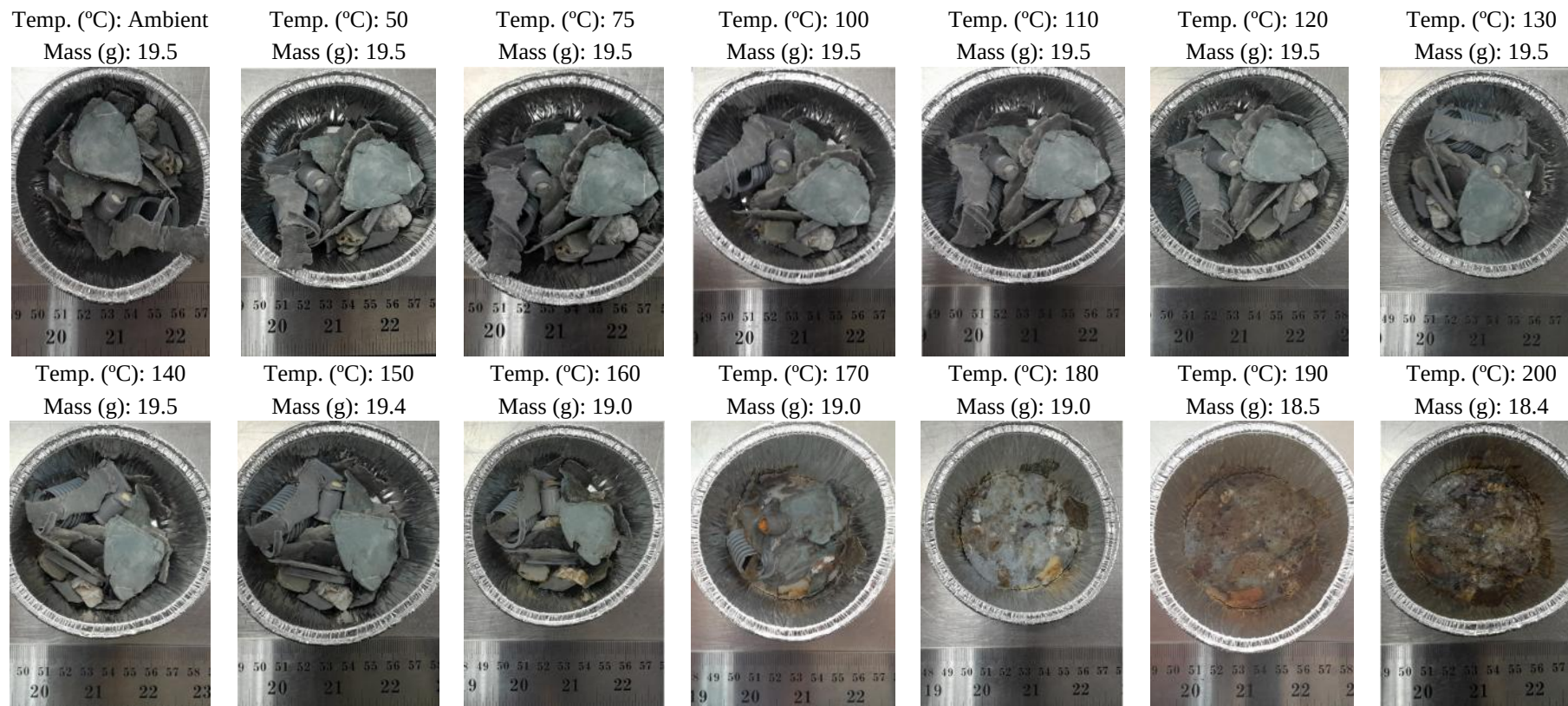


Figure A.8.4 - Sample F – Floating rigid grey plastics

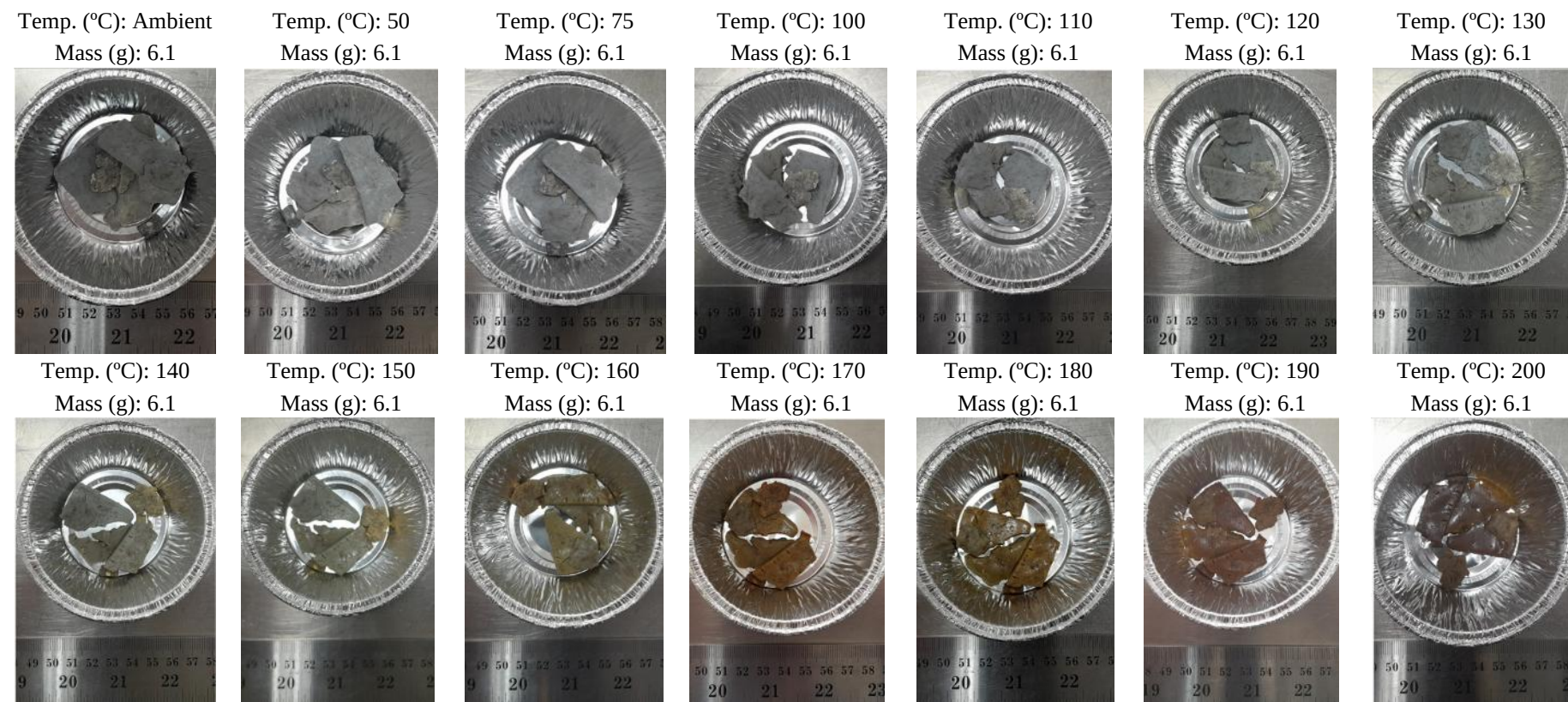


Figure A.8.5 - Sample F – Non rigid grey plastics

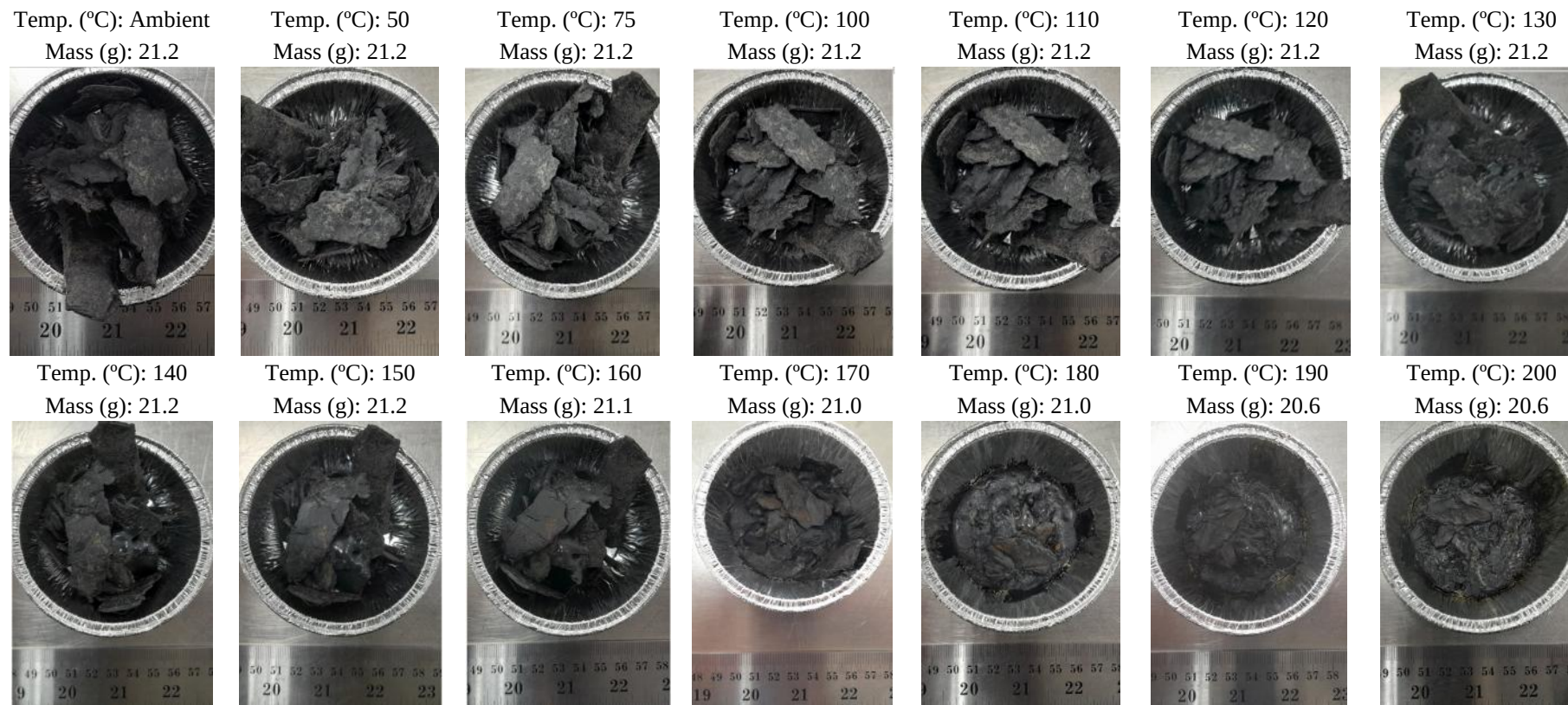


Figure A.8.6 - Sample F – Floating rigid black plastic

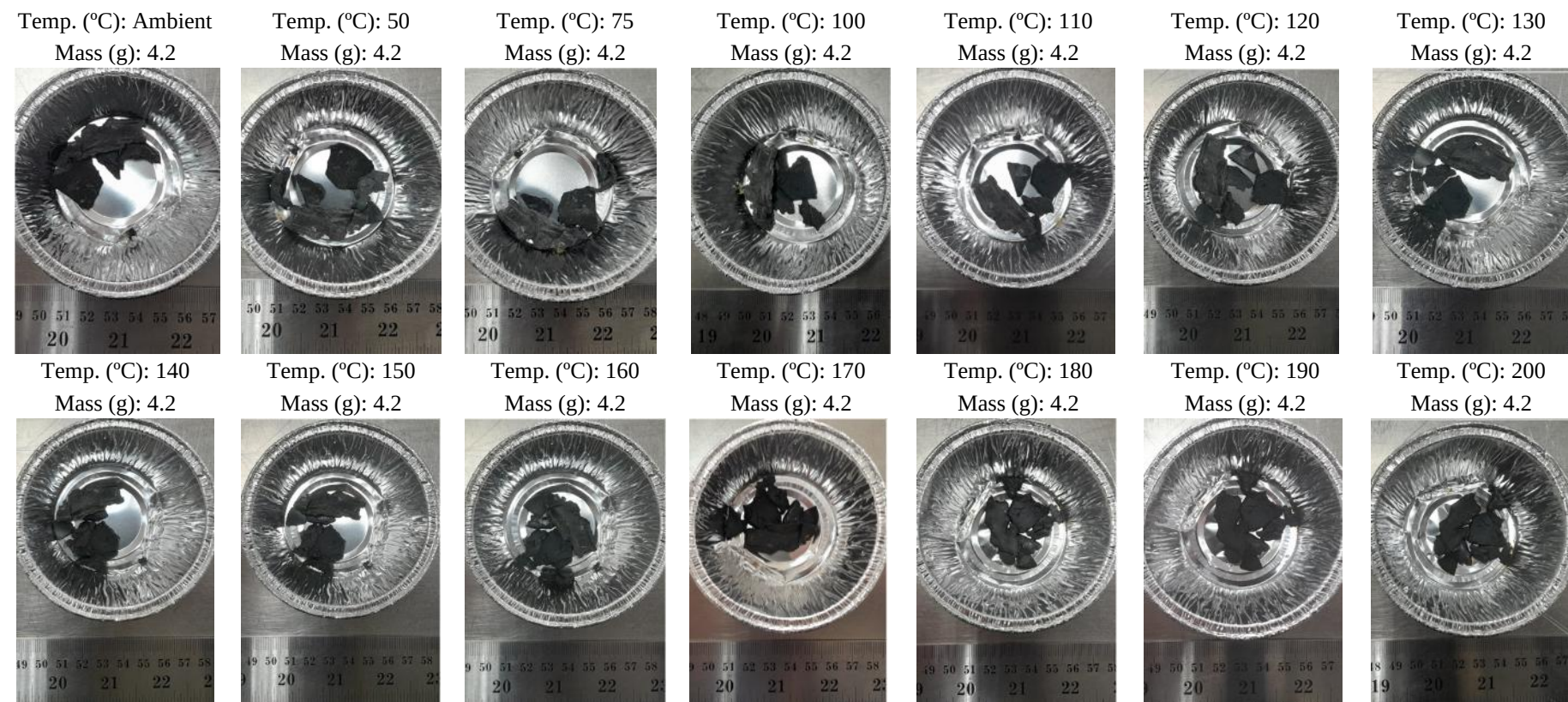


Figure A.8.7 - Sample F – Non floating rigid black plastic

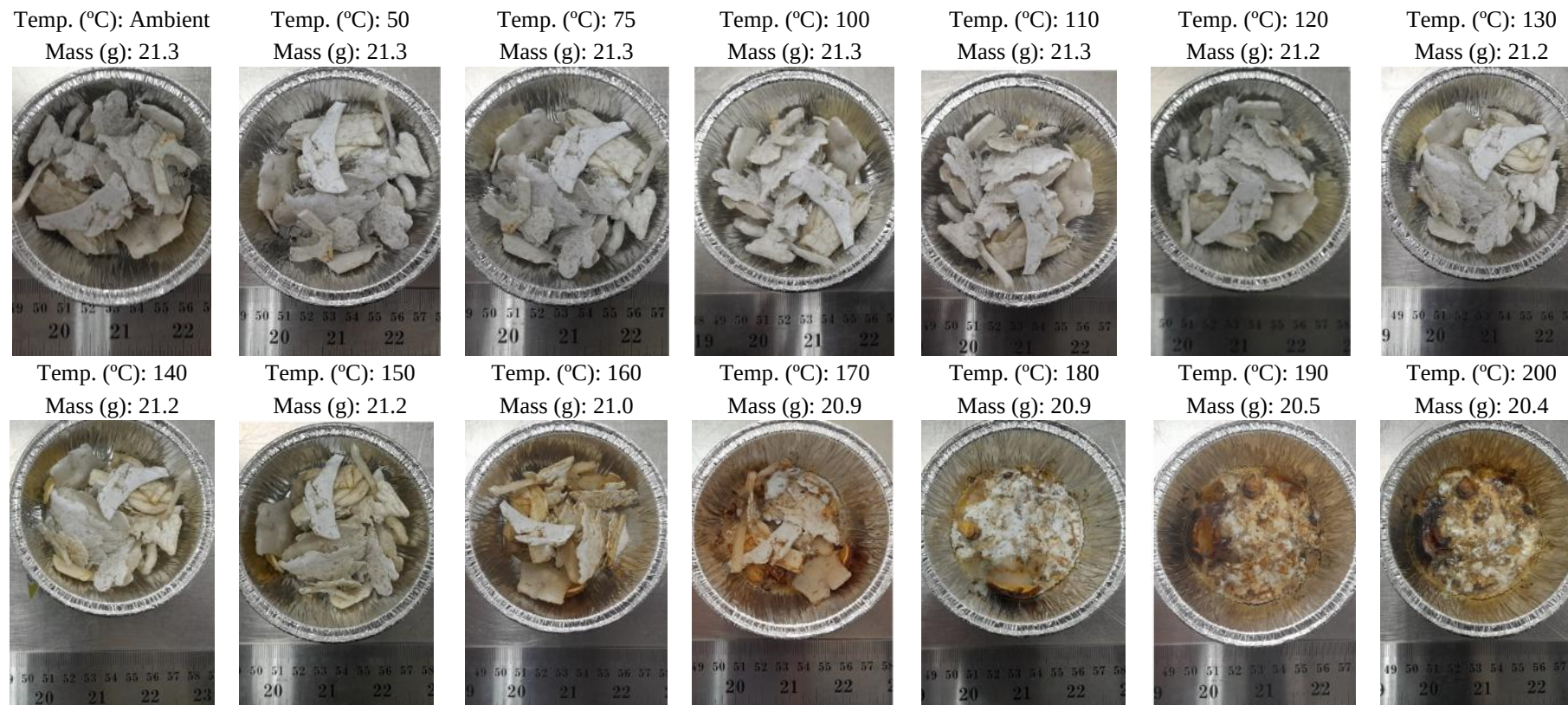


Figure A.8.8 - Sample F – Floating rigid white plastics



Figure A.8.9 - Sample F – Non floating rigid white plastics

Annex 9: Melting point of sample G

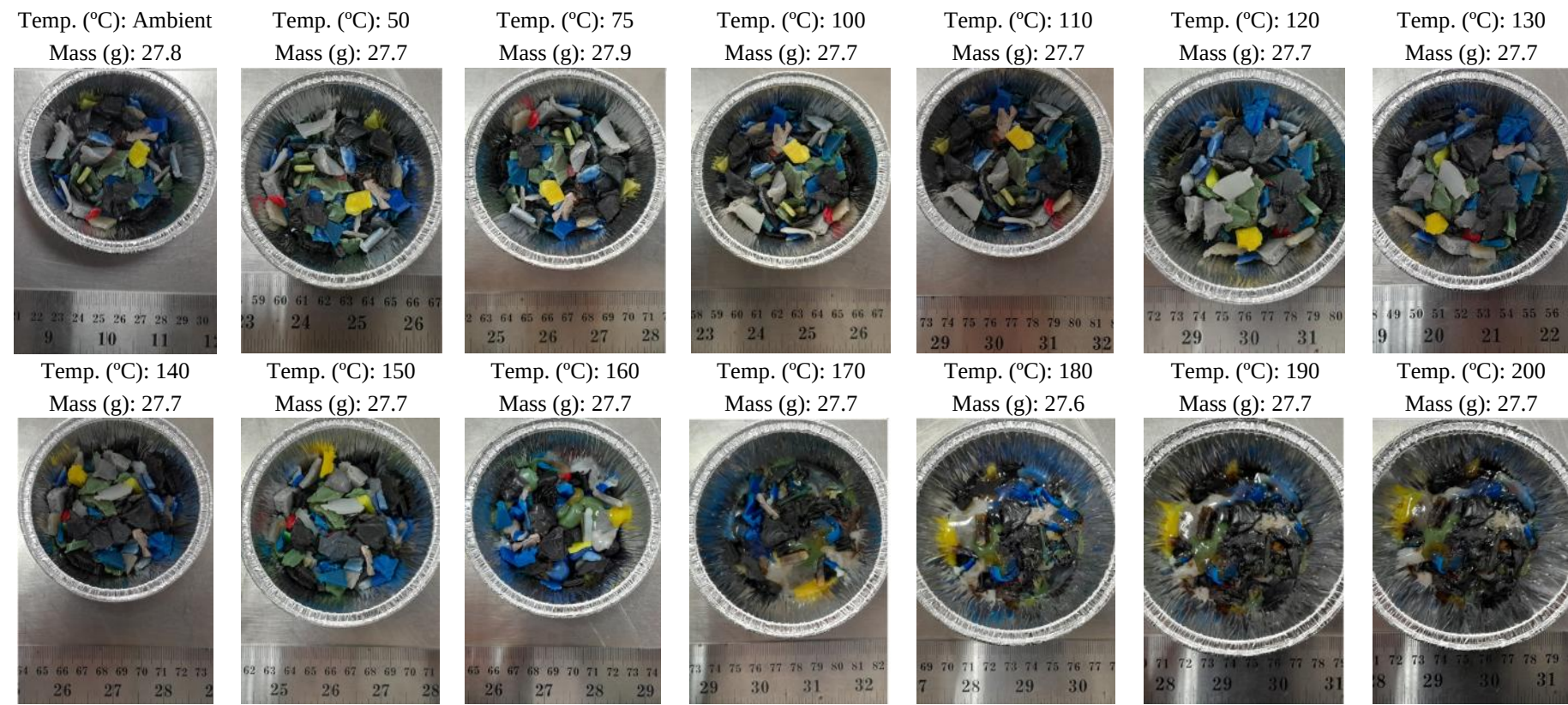


Figure A.9.1 - Sample G – HDPE

Annexe 10: Melting point of sample H

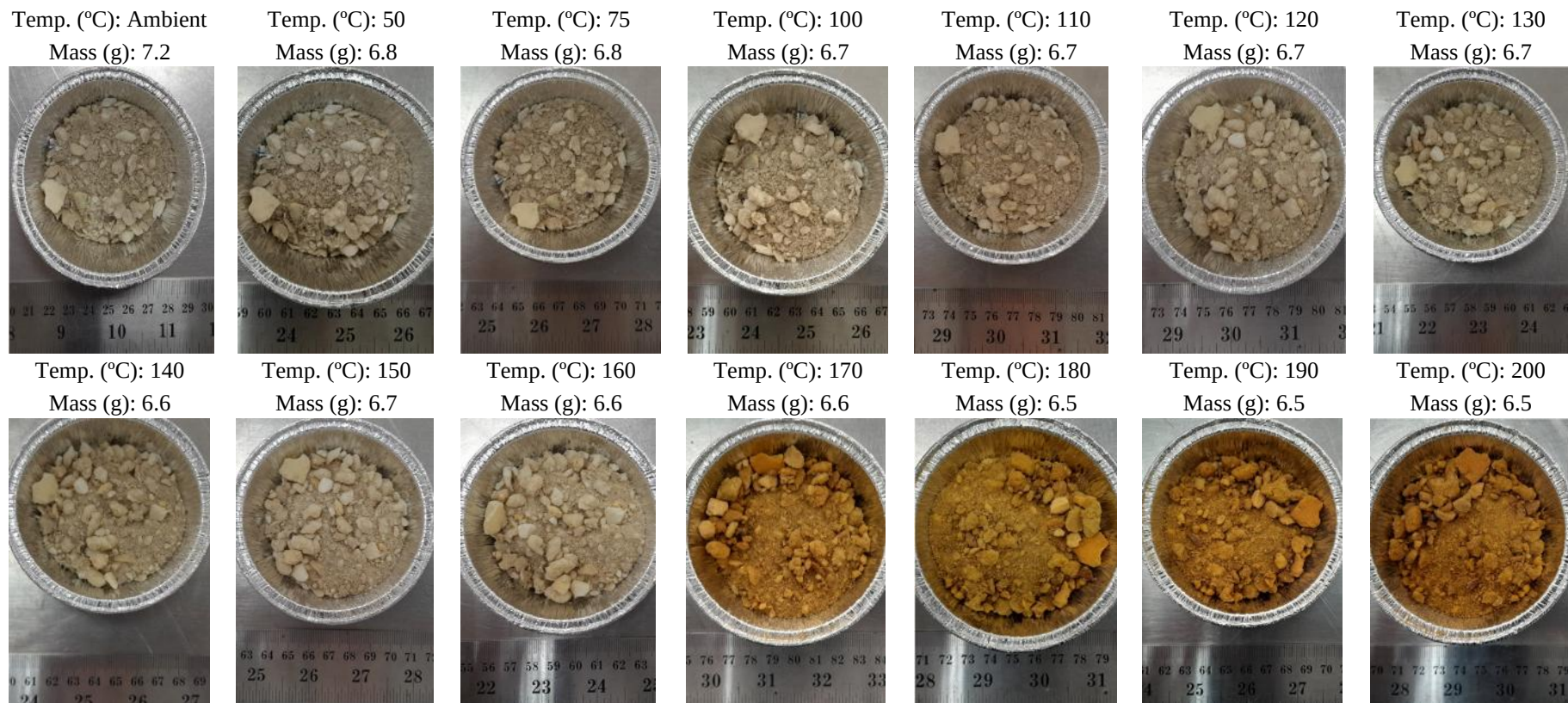


Figure A.10.1 - Sample H – Polyurethane

Annexe 11: Melting point of sample I

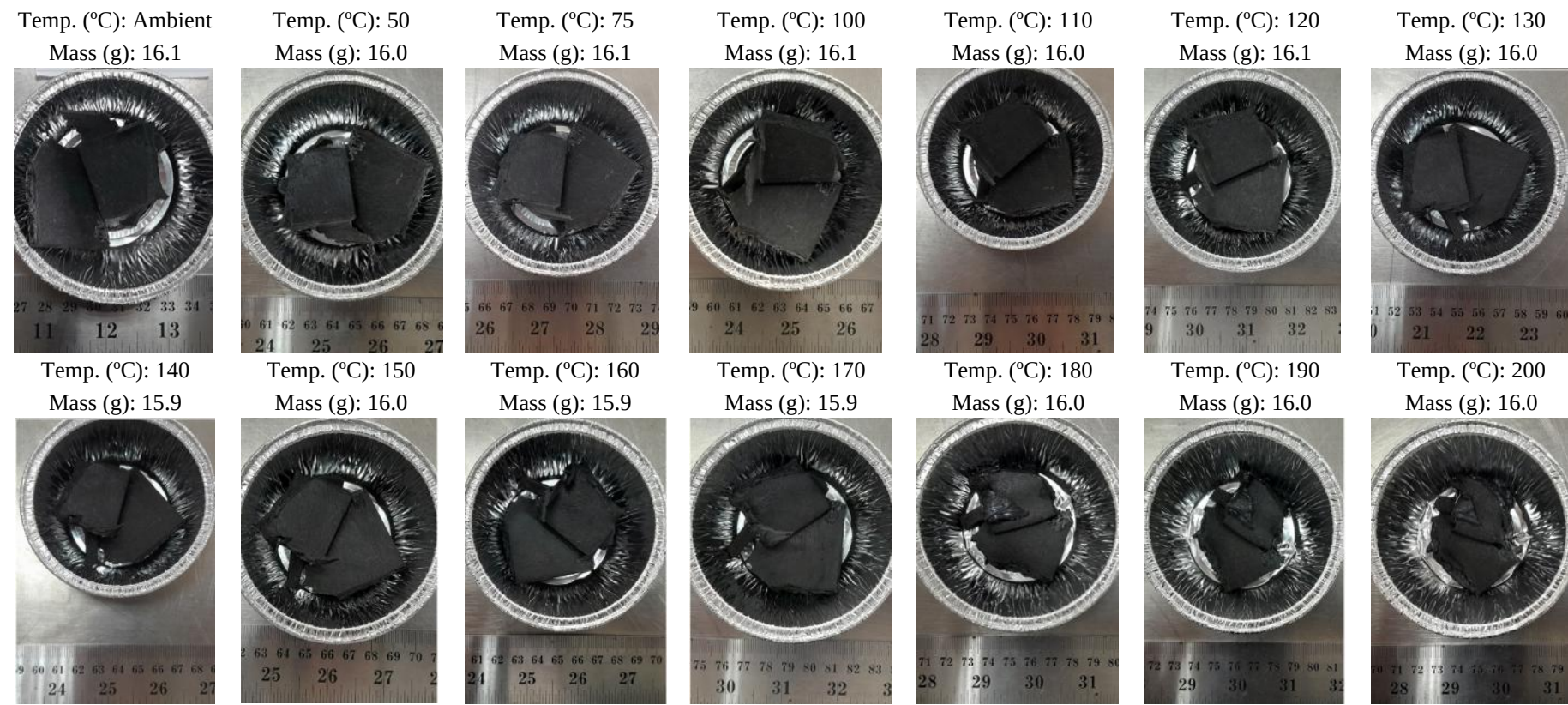


Figure A.11.1 - Sample I – Pallet

Annexe 12: Melting point of sample J

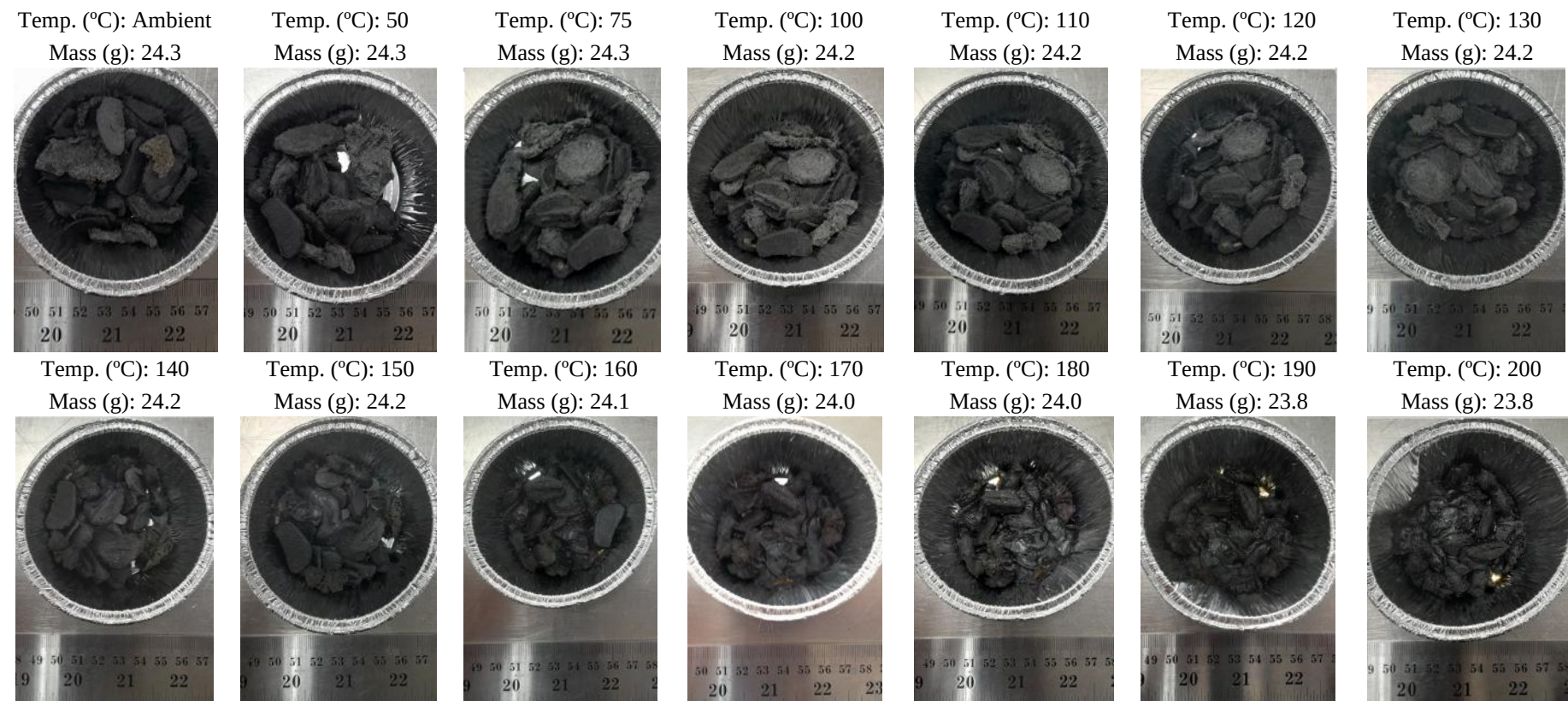


Figure A.12.1 - Sample J – Floating rigid black plastic

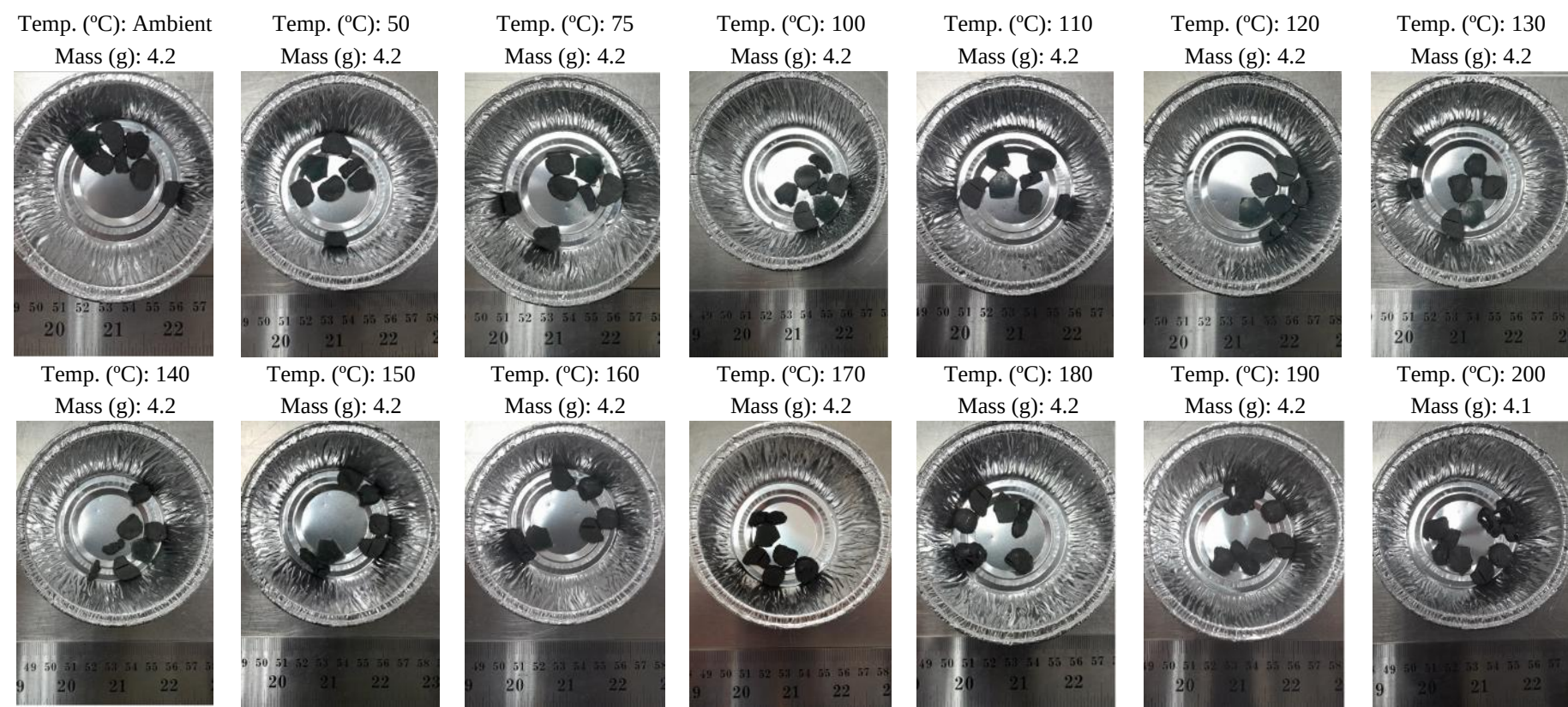


Figure A.12.2 - Sample J – Non floating rigid black plastic

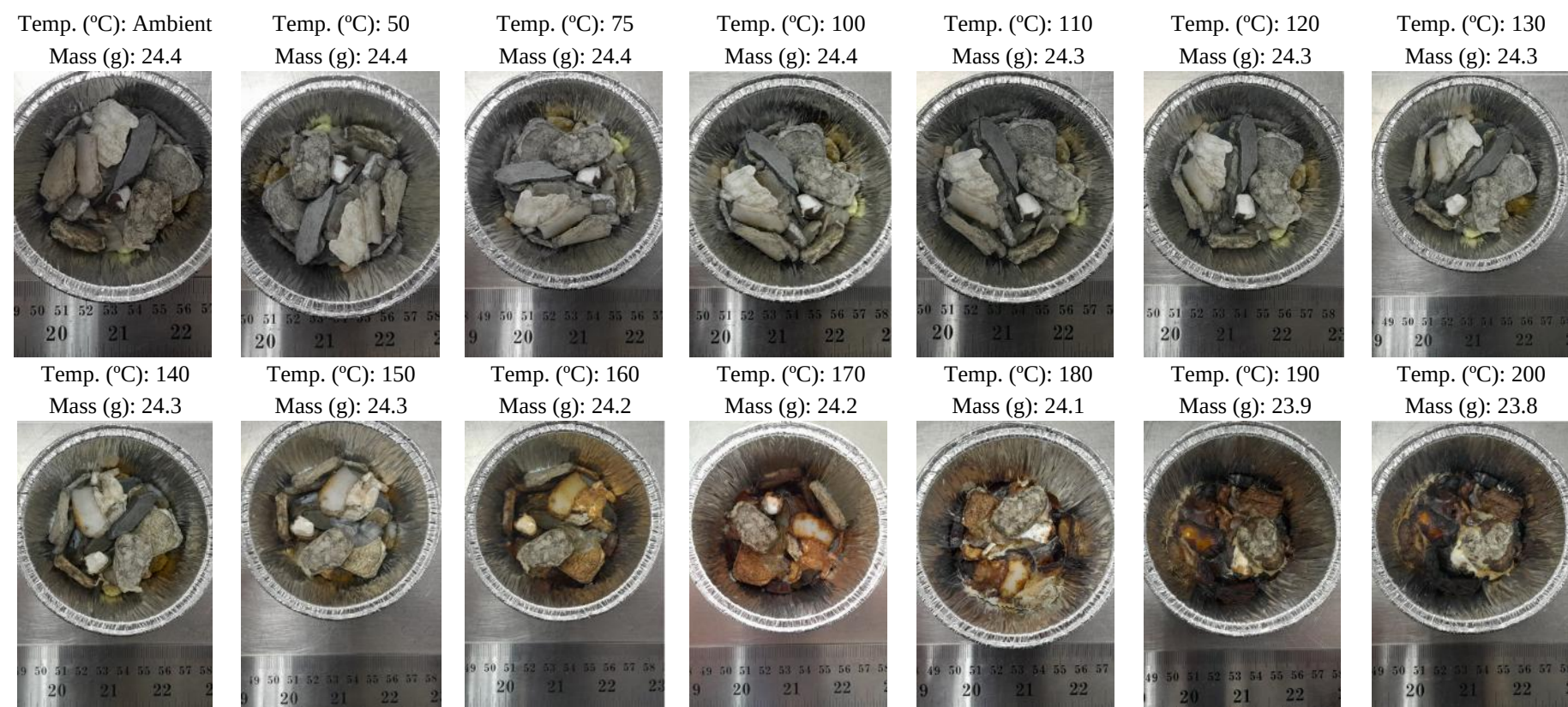


Figure A.12.3 - Sample J – Floating rigid white plastics

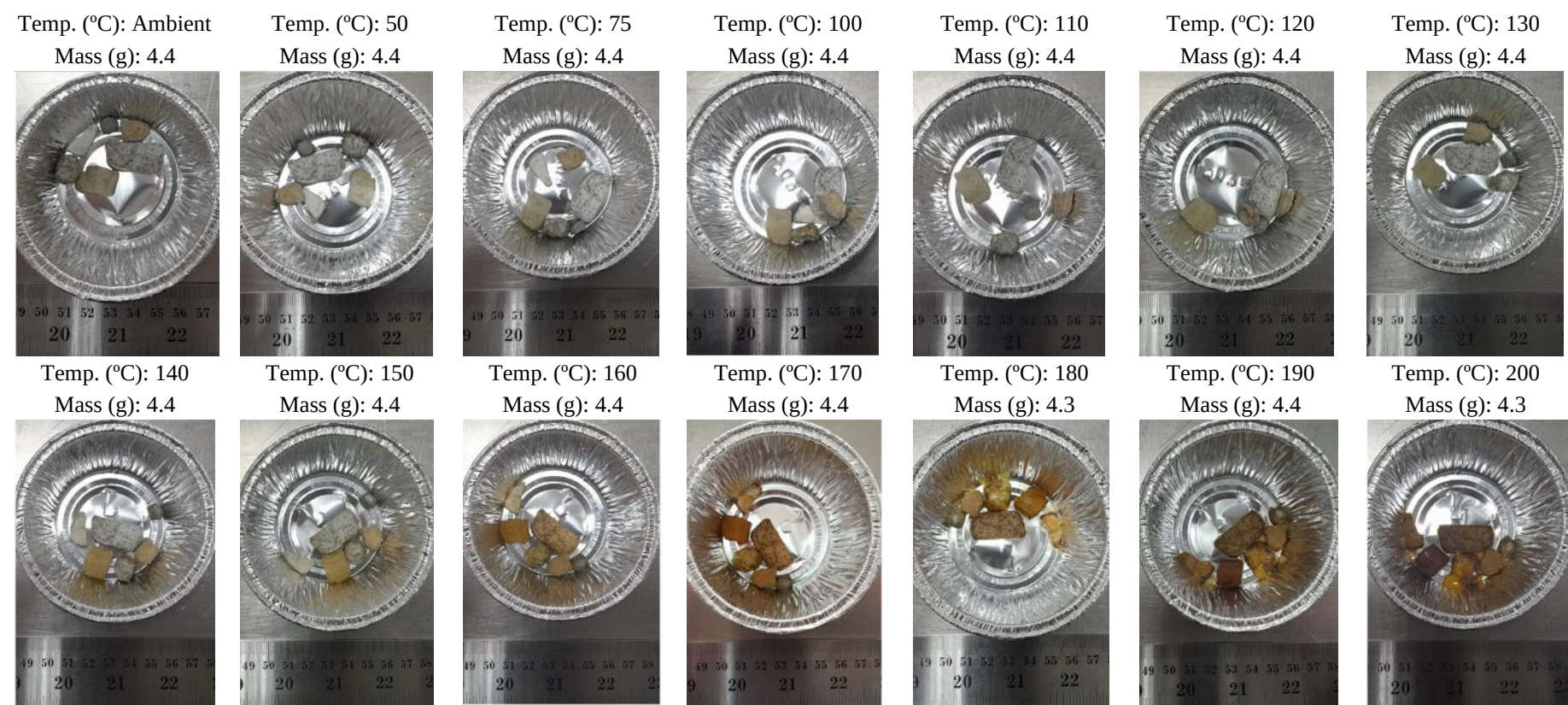


Figure A.12.4 - Sample J – Non floating rigid white plastics

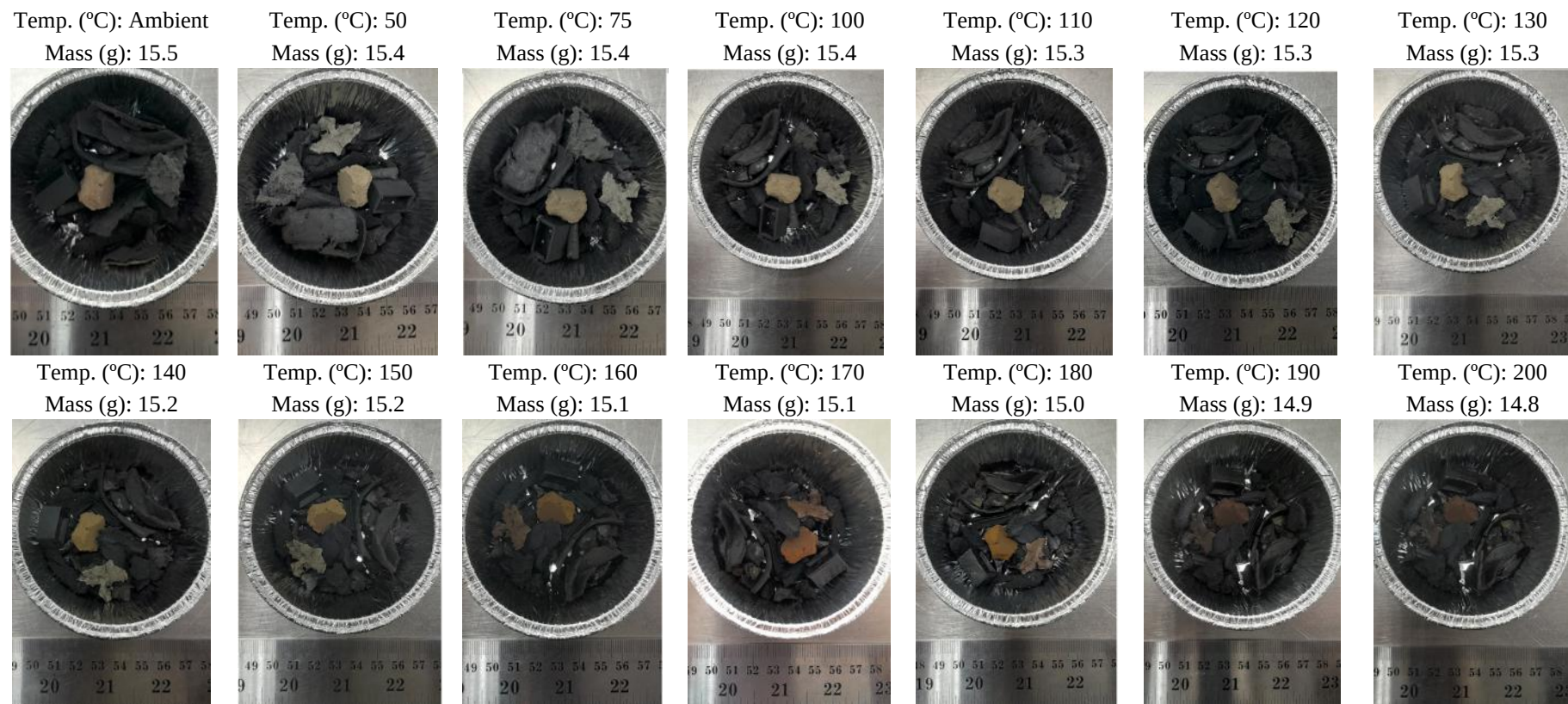


Figure A.12.5 - Sample J – Floating rubber

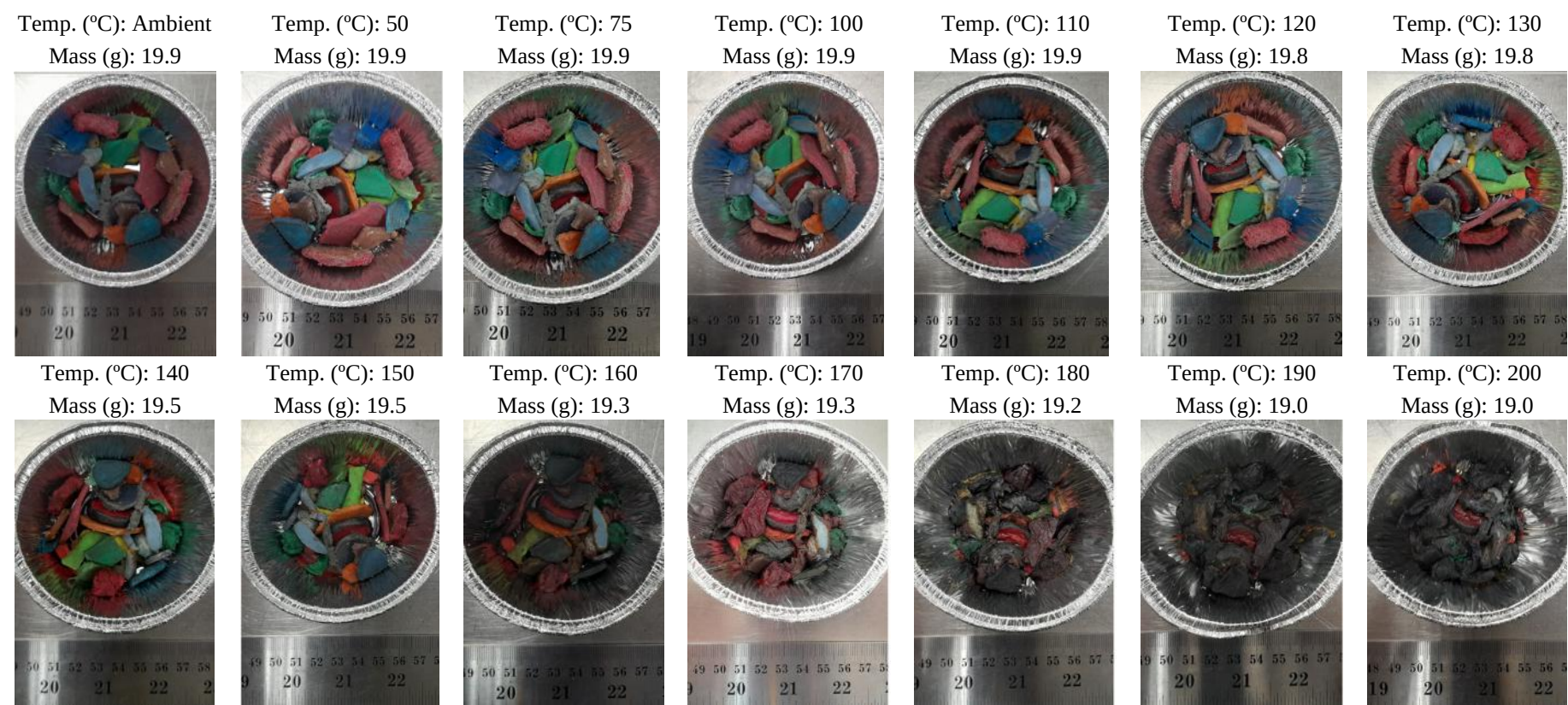


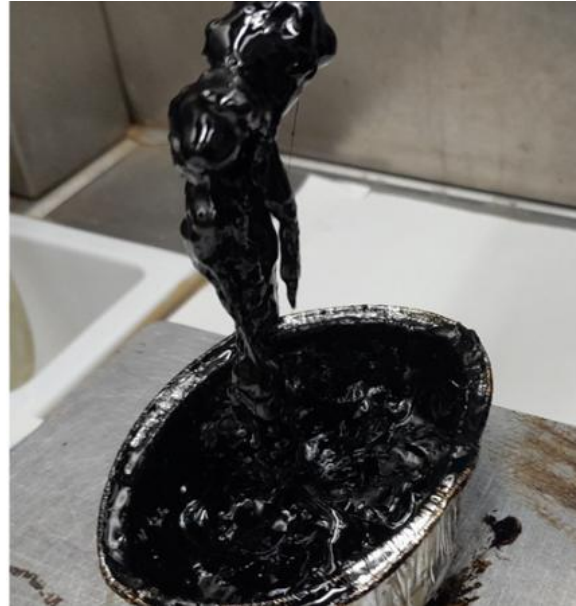
Figure A.12.6 - Sample J – Floating rigid coloured plastics

Annex 13: Incorporation with Bitumen

Addition to 10% at 150 °C



Addition to 20% at 150 °C



90 minutes at 180 °C

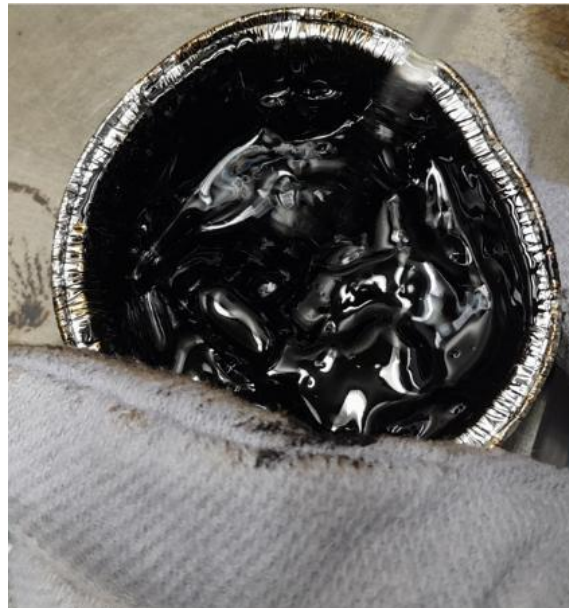


Figure A.13.1 - Sample B – Incorporation with bitumen

Addition to 10% at 150 °C



Addition to 20% at 150 °C



90 minutes at 180 °C



Figure A.13.2 - Sample D – Incorporation with bitumen

Addition to 10% at 150 °C



Addition to 20% at 150 °C



90 minutes at 180 °C



Figure A.13.3 - Sample G – Incorporation with bitumen

Addition to 10% at 150 °C



Addition to 20% at 150 °C



90 minutes at 180 °C



Figure A.13.4 - Sample H – Incorporation with bitumen

Annexe 14: Geometric Density Results

Table A.14.1 - Geometric density results

Bitumen content (%)		3.5				4.0				4.5			
Specimen identification		1	2	3	4	1	2	3	4	1	2	3	4
h	(mm)	63.8	64.0	64.5	63.6	63.0	63.8	64.6	62.4	65.2	64.1	62.8	65.1
Φ	(mm)	101.1	101.1	100.8	100.9	101.2	101.2	101.3	101.2	101.5	101.3	101.4	101.6
m ₁	(g)	1065.9	1063.0	1064.5	1066.6	1054.8	1058.4	1066.4	1060.8	1061.7	1066.8	1069.2	1062.2
v	(mm ³)	5.12E+05	5.14E+05	5.14E+05	5.09E+05	5.07E+05	5.13E+05	5.20E+05	5.02E+05	5.28E+05	5.17E+05	5.07E+05	5.28E+05
Geometric density	(Mg/m ³)	2.08	2.07	2.07	2.10	2.08	2.06	2.05	2.11	2.01	2.07	2.11	2.01

Annexe 15: Bulk Density Results

Table A.15.1 - Bulk density results

Bitumen content (%)		3.5				4.0				4.5			
Specimen identification		1	2	3	4	1	2	3	4	1	2	3	4
t	(°C)	18.9	18.9	18.9	18.9	18.9	18.9	18.9	18.9	18.9	18.9	18.9	18.9
m ₁	(g)	1065.9	1063.0	1064.5	1066.6	1054.8	1058.4	1066.4	1060.8	1061.7	1066.8	1069.2	1062.2
ρ _w	(Mg/m ³)	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998
m ₂	(g)	564.0	564.2	562.9	563.3	560.1	567.3	551.8	574.0	548.8	568.8	576.3	541.2
m ₃	(g)	1066.7	1063.4	1066.0	1067.2	1055.7	1061.1	1067.5	1062.6	1062.7	1069.1	1071.1	1063.5
Bulk density	(Mg/m ³)	2.12	2.13	2.11	2.11	2.13	2.14	2.06	2.17	2.06	2.13	2.16	2.03

Annexe 16: Maximum Density Results

Table A.16.1 - Maximum density results

Bitumen content (%)		3.5	4.0	4.5
m ₄	(g)	1386.4	1386.5	1386.5
m ₆	(g)	2647.5	2487.9	2562.6
m ₇	(g)	12376.6	12280.8	12324.7
t	(°C)	22.0	22.0	22.0
ρ _w	(Mg/m ³)	0.9978	0.9978	0.9978
Maximum density	(Mg/m ³)	2.268	2.239	2.249

Annex 17: Marshall Results

Table A.17.1 - Marshall results

Bitumen content (%)	3.5	4.0	4.5
Density [Mg/m ³]	2.117	2.125	2.095
Maximum corrected stability [kN]	16.5	16.6	16.1
Deformation [mm]	3.8	3.8	3.8
Tangential deformation [mm]	1.8	1.8	1.8
Total deformation [mm]	4.1	4.1	4.1
Marshall quotient [kN/mm]	4.5	4.5	4.3

Annexe 18: Porosity and VMA Results

Table A.18.1 - Porosity and VMA results

Bitumen content (%)	3,5				4.0				4,5			
Specimen identification	1	2	3	4	1	2	3	4	1	2	3	4
Porosity (%)	6.651	6.253	6.848	6.812	5.086	4.415	7.783	3.179	8.277	5.331	4.064	9.710
Average porosity (%)	6.641				5.116				6.845			
Bitumen density (Mg/m³)	1.01											
VMA(%)	13.99	13.621	14.170	14.136	13.50	12.891	15.960	11.764	17.47	14.817	13.677	18.757
Average VMA (%)	13.979				13.529				16.180			

Annex 19: Water sensitivity - Results

Table A.19.1 - Water sensitivity – Results

Specimen identification		1	2	4	3	5	6
h	(mm)	64.6	64.5	62.4	63.6	64.3	64.1
Φ	(mm)	101.6	101.4	101.7	101.5	101.4	101.5
v	(cm ³)	523.94	521.09	506.46	514.53	519.25	519.21
m ₁	(g)	1066.5	1055.4	1058.3	1057.5	1059.1	1073.2
m ₂	(g)	574.2	550.5	581.9	557.3	564.8	593.3
m ₃	(g)	1070.8	1056.0	1059.8	1058.3	1059.6	1077.8
Bulk density	(Mg/m ³)	2.145	2.085	2.212	2.108	2.138	2.212
v ₂	(cm ³)	-	-	-	511.3	518.1	517.1
Δv	(%)	-	-	-	0.6	0.2	0.4
Maximum resistance	(kN)	16.03	18.24	20.74	18.24	19.75	17.74
Average maximum resistance	(kN)	18.337			18.577		
Indirect traction	(Gpa)	0.00155	0.00178	0.00208	0.0018	0.00193	0.00173
Average indirect traction	(Gpa)	0.0018			0.00182		
Preserved strength in indirect traction	(%)	101.0					
Type of failure		c	b	a	b	c	b

Annexe 20: Water sensitivity - Type of failure



Figure A.20.1 - Specimen 1 – Type of failure



Figure A.20.2 - Specimen 2 - Type of failure



Figure A.20.3 - Specimen 3 - Type of failure



Figure A.20.4 - Specimen 4 - Type of failure



Figure A.20.5 - Specimen 5 - Type of failure



Figure A.20.6 - Specimen 6 - Type of failure

Annex 21: Wheel tracking results

Table A.21.1 - Wheel tracking results

	Bituminous mixture with plastic			Reference mixture		
	Slab 1	Slab 2	Average	Slab 1	Slab 2	Average
RD_{AIR} [mm]	0.3	0.1	0.2	5.78	6.04	5.91
WTS_{AIR} [mm/10³ cycles]	0.0	0.0	0.0	0.27	0.29	0.28
PRD_{AIR} [%]	0.5	0.1	0.3	11.34	12.03	11.685

Annexe 22: Fatigue resistance results

Table A.22.1 - Fatigue resistance results

Bituminous mixture with plastic		Reference mixture	
Extension [ε]	Number of cycles	Extension [ε]	Number of cycles
400	936000	200	420018
400	59600	200	287655
400	255900	200	588359
400	75100	300	81521
500	71200	300	101085
500	4100	300	83380
500	3300	400	21580
500	703700	400	18149
600	6600	400	12545
600	479600		
600	525500		

Annex 23: Wear course characteristics

Table A.23.1 - Wearing course characteristics

Surface course characteristics			
Property	Unit	AC 14 surf 35/50	Bituminous mixture with plastic
Thickness	[m]	0.06	
Width	[m]	8.0	
Length	[m]	1000.0	
Volume	[m ³]	480.0	
Bulk density	[Mg/m ³]	2.56	2.19
Required mass	[Mg]	1228.8	1051.2

Annex 24: Cost of reference mixture and mixture with plastic

Table A.24.1 - Cost of reference mixture and mixture with plastic

Constituent	AC 14 Surf 35/50			Bituminous mixture with plastic		
	Mass [Mg]	Unit price [€/Mg]	Cost (€)	Mass [Mg]	Unit price [€/Mg]	Cost (€)
Bitumen	58.5	976.0	57109.9	42.4	976.0	41353.9
Basalt 10/16	280.9	15.0	4213.0	242.1	15.0	3631.8
Basalt 4/12	386.2	15.0	5792.9	332.9	15.0	4993.7
Limestone 0/4	339.4	16.0	5430.1	191.7	16.0	3066.8
Basalt 0/4	128.7	15.0	1931.0	111.0	15.0	1664.6
Commercial filler	35.1	15.0	526.6	30.3	15.0	454.0
Plastic	0.0	0.0	0.0	100.9	0.0	0.0
Total	1228.8	-	75003.6	1051.2	-	55164.8