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SMILE CITY

Sustainable Materials for Innovative, Low Emissions applications in the CIrcular ciTY

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SMILE CITY Book: “Enhance the sustainability and quality of urban furniture in cycling lanes while promoting eco-friendly materials and innovative design”

By RECYKL

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1 EXECUTIVE SUMMARY

1.1 Purpose of the deliverable

Upon completion of the project, this deliverable will be published as a publicly accessible SMILE CITY Book entitled: “Enhance the Sustainability and Quality of Urban Furniture in Cycling Lanes while Promoting Eco-Friendly Materials and Innovative Design.”
The publication is intended for public administration stakeholders, with a particular focus on technical professionals responsible for the design and maintenance of cycling infrastructure and road systems. Its objective is to raise awareness of the benefits associated with the use of materials derived from end-of-life tyres (ELTs) in the production of sustainable, cost-effective urban furniture.

1.2 Brief description of activities and results

This study evaluates the technical feasibility, performance, and sustainability potential of materials derived from end-of-life tyres (ELTs) for use in urban cycling infrastructure, alongside recommendations for improving recycling systems and material processing. Activities covered Product search and producer identification, Sustainability enhancement, Material characterization and Testing.

1.2.1 Applicability of ELT-Derived Materials

The results confirm that ELT-derived materials—namely crumb rubber, rubber powders, and textile fibres—can be effectively incorporated into both thermoplastic (HDPE, PP, LDPE) and elastomeric matrices, enabling their use in a wide range of urban cycling infrastructure products.

Key applications include:
Bollards (including elastic and impact-resistant types)
Lane separators and modular kerbs
Speed control elements and traffic calming systems
Rubber curbs, tiles, and drainage components
Signage bases and protective infrastructure elements

Mechanical performance:
Required mechanical thresholds for such applications are relatively low (≈2 MPa tensile strength), allowing high substitution levels of virgin materials
Advanced processing methods (devulcanization, compounding) significantly improve performance
Melt-blended thermoplastics demonstrate:

1. Tensile strength retention of 65–87%
2. Enhanced impact resistance, exceeding virgin polymers (up to ~172%)

Material efficiency:
Rubber compounding enables high-performance materials with >70% recycled content
Textile fibres function as highly effective reinforcing fillers, outperforming conventional mineral fillers
Fine rubber powders enhance compatibility and mechanical performance

Environmental and economic benefits:
ELT-derived materials exhibit very low or negative carbon footprint (GWP)
Substitution of virgin polymers results in:

1. Up to 6× material cost reduction
2. Significant CO_2 savings (up to ~13× reduction vs virgin polymers)

1.2.2 Required Improvements in Recycling Methods and Infrastructure

The study identifies key areas for optimization to unlock the full potential of ELT-derived materials.

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Feedstock preparation:
Tyre sorting (by type, composition, and application) is critical but currently underutilized.
Automated sorting systems are recommended to ensure consistent material quality.

Material recovery:
Tyre deconstruction enables separation of chemically distinct components (tread, carcass, liner), improving downstream performance.
Enhanced textile and contaminant removal systems are required, especially for fine fractions.

Process optimization:
Transition from fixed/random to adjustable feeding systems allows control of material composition and final properties.
Improved granulation and powderisation processes enable production of high-quality fine powders.

Utilization of secondary streams:
Fine fractions (subsieve powders) require better purification or targeted applications due to contamination issues.

1.2.3 Strategic Conclusions

ELT-derived materials represent a technically viable, cost-effective, and environmentally superior alternative to virgin materials in urban cycling infrastructure. Their performance is sufficient—and in some cases superior—for impact-critical applications.
The key to successful implementation lies in process control, feedstock quality, and material engineering, rather than material substitution alone.
The study supports the integration of ELT recycling into circular urban infrastructure systems, contributing to:

1. reduced environmental footprint
2. lower material costs
3. improved sustainability compliance (EUDR, CSRD, net-zero targets)

2 ACTIVITIES CARRIED OUT

2.1 Identification of urban furniture products

2.1.1 The overview of cycling-path and road “urban furniture” commonly sold on the market

Cycling-path and road “urban furniture” commonly sold on the market could be classified using following functional description:

1. Separation + protection (core cycling-path kit)
    a. Bollards (fixed / removable / flexible / illuminated) – access control, anti-parking, edge protection.
    b. Cycle-lane separators / modular kerbs / lane dividers (bolt-down, modular, recycled plastic/rubber, polymer concrete).
    c. Delineator posts / flexible “wands” / reflective posts (often paired with separators).
    d. Barriers + guardrails (edge protection, pedestrian–cycle separation, chicanes, access control).
2. Parking + cyclist services
    a. Bike racks / stands (U-racks, hoop racks, wave racks, integrated rack+bollard hybrids).
    b. Shelters / covered parking (bike canopies; sometimes with charging/lockers).
3. Safety + legibility
    a. Wayfinding posts / totems / signage supports (route markers, direction signs; often bundled with lighting).
    b. Reflective markers / hazard markers (vertical markers, reflective strips, etc.).
4. Comfort + streetscape elements commonly included in cycling projects
    a. Benches / rest points, bins, planters, drinking fountains (often installed along greenways and protected routes).

2.1.2 Example of producers of urban furniture from Europe, Turkey and Serbia

Below listed are manufacturers and producer-brands grouped by product category and covering Europe, Turkey, and the Balkans / SE Europe. The priority was for companies with public product pages, as well as known to project partners including cities and relevant to cycle-lane separators, bollards, bike parking, shelters, and adjacent street furniture.

2.1.2.1 Lane separators, delineators, flexible posts, cycle-lane defenders

1. ZICLA (Spain) — cycle-lane separators / planters, “Zebra Family.”
2. Geyer-Hosaja (Poland) – road bollards, elastic vulcanised bollards, rubber curbs, ”brail” rubber tiles, base for road signs, anti-vegetation mats, blades for snowploughs, asylum segments, lane separators, speed bumps for scooters and vehicles.
3. Ado Urban Furniture (Spain) — rubber and recycled-plastic cycle-lane defenders, flexible bollards.
4. Rediweld Traffic (UK) — ORCA cycle-lane separator range.
5. Leafield Highway (UK) — cycle-lane bollards and active-travel delineation products.
6. PWS Signs (Ireland / UK) — VeloKerb, flexible bollards, Tiger separators.
7. Traffic Innovation (Canada/Europe-active supplier) — DEFLEX flexible bike-lane delineators / bollards.
8. Melba Swintex (UK) — Road Runner separator, recycled-content temporary / semi-permanent delineation.
9. Broxap (UK) — cycle-lane PU bollards and broader active-travel hardware.
10. İlgi Trafik (Turkey) — plastic road separators and delineators.
11. İleri Trafik (Turkey) — plastic separator curbs with delineators.
12. MFK Plastik (Turkey) — delineators, warning posts, barriers, pedestrian posts.
13. Biri Group (Turkey) — traffic separators with delineators / road separator line.
14. Zeplin Traffic Safety Solutions (Turkey) — lane separators, delineators, warning sign poles.
15. Sinyalizasyon Elektronik (Turkey) — delineators and broader traffic-safety products.
16. Top-rubber (Germany) – lane separators, curb ramps, tire shoes

17. GPR Zarzecze (Poland) – rubber curbs, parking separators

2.1.2.2 Bollards, posts, barriers, and multifunctional cycle-project hardware

1. Metalco (Italy) — bollards, including dual-use bollard / bike-rack designs.
2. LAB23 (Italy) — HI BOLLARD and related steel street-furniture elements for bike parking / access control.
3. mmcité (Czechia) — bollards plus bicycle and scooter stands.
4. BENKERT BÄNKE (Germany) — stainless-steel bike stands and related outdoor furniture.
5. HITSA (Denmark) — bicycle bollards, cargo-bike parking, bollards and barriers.
6. Procity (France) — bollards plus bicycle stands / shelters.
7. Urbidermis (Spain) — bollards, bicycle racks, and hybrid bollard-rack products.
8. Vestre (Norway) — cycle parking and urban bollards.
9. Neri (Italy) — bicycle racks and bollards within its street-furniture collections.
10. Furnitubes (UK) — cycle parking and broad bollard portfolio.
11. HAGS (Sweden) — bicycle racks and bollard-style cycle stands.
12. Husson (France) — mobility equipment, bicycle parking, bollards, and barriers.
13. Streetlife (Netherlands) — bollards, bicycle parking, and bicycle bridges / public-space systems.
14. Venag (Poland) — bike storage / repair solutions and bollards.
15. Calzolari (Italy) — concrete bollards and bike racks.
16. Mertoğlu (Turkey) — bike racks, outdoor bollards, barriers, and wider urban furniture.
17. Gran-Tech (Poland) – modular drainage system for cycling paths
18. Pilomat (Italy) – automatic/retractable bollards (access control / perimeter security).
19.

2.1.2.3 Bike racks, bicycle stands, shelters, and secure cycle parking specialists

1. VelopA (Netherlands) — bicycle parking systems, shelters, street furniture, bollards.
2. Falco (Netherlands/Poland/UK) — bicycle parking, shelters, bollards, traffic guides.
3. Cyclehoop (UK) — Bikehangars, shelters, racks, repair stations, on-street cycle parking.
4. Broxap (UK) — commercial cycle parking, shelters, hubs, racks, stands.
5. Procity (France) — bicycle racks, stands, shelters, secure shelters.
6. HITSA (Denmark) — bicycle bollards / stands and cargo-bike parking.
7. BENKERT BÄNKE (Germany) — bike stands for public-realm and workplace schemes.
8. mmcité (Czechia) — bicycle and scooter stands, bicycle shelters & canopies.
9. Cervic Environment (Spain) — bike racks and recycled urban furniture.
10. Metalfabrik (EU-based producer) — bike racks, bollards, shelters, street furniture.
11. HAGS (Sweden) — bicycle racks / storage products.
12. Husson (France) — hoops, racks, terminals, secure bicycle parking.
13. Urbidermis (Spain) — bicycle racks as part of its urban furniture system.
14. Vestre (Norway) — cycle-parking product family.
15. Neri (Italy) — bicycle-rack typology within its street-furniture range.

2.1.2.4 Broad urban-furniture manufacturers that frequently fit cycling-path projects.

These are useful when a project needs bike parking, bollards, benches, bins, planters and wayfinding from fewer suppliers.

1. Cervic Environment (Spain) — bollards, fences, bike racks, recycled urban furniture.
2. Urbidermis (Spain) — bicycle racks, bollards, handrails, parking stoppers, broader public-realm catalog.
3. Streetlife (Netherlands) — street furniture, bicycle parking, small pedestrian / bicycle bridges.
4. VelopA (Netherlands) — street furniture, bicycle parking systems, bollards, shelters.
5. Procity (France) — street furniture, bollards, bicycle solutions.
6. Broxap (UK) — street furniture, signage, shelters, cycle parking, bollards.
7. HAGS (Sweden) — park & urban furniture plus bicycle storage lines.

8. Husson (France) — complete street-furniture and mobility range.
9. Calzolari (Italy) — concrete urban furniture, including bike racks and bollards.
10. Metalco (Italy) — street furniture with cycling-relevant bollards / bike-rack hybrids.

2.1.2.5 Selected Balkans and SE Europe manufacturers

1. Meteor Beograd (Serbia) — urban furniture including barricade bollards, bike holders, fences.
2. Urbana Oprema (Serbia) — urban equipment producer based in Novi Sad.
3. Tiha d.o.o. (Serbia) — concrete urban furniture and bicycle stands.
4. Metalgan (Romania) — urban furniture producer with bike racks, delineation posts, bollards.
5. Vidas Met (Romania) — urban furniture producer with bicycle racks.
6. Smits (Romania) — producer of steel bicycle racks for public spaces.
7. ATRIVA (Slovenia) — urban equipment incl. bike stands, bollards, info boards, e-bike service / charging points.
8. Urbana Oprema (Slovenia) — bike racks and other outdoor equipment.
9. EKI Kranj (Slovenia) — inox bike stands and street bollards.
10. TFM TIM (Serbia) – produces/markets parking barriers (useful for access control around cycle infrastructure and adjacent parking).

2.1.2.6 Selected Turkish producers:

1. Mertoğlu (Turkey) – urban furniture product families explicitly include bike racks, outdoor bollards, and barriers.
2. İlgi Trafik / Interest Traffic Systems (Turkey) – flexible delineators / plastic road separators (lane separation + guidance).
3. Turkish Manufacturers directories (Turkey) – exporter/manufacturer listings for bollards and for delineators / lane dividers (useful for supplier discovery/shortlisting).
4. MFK Plastik (Turkey) — delineators, warning posts, barriers, pedestrian posts.
5. Biri Group (Turkey) — traffic separators with delineators / road separator line.
6. Zeplin Traffic Safety Solutions (Turkey) — lane separators, delineators, warning sign poles.
7. Sinyalizasyon Elektronik (Turkey) — delineators and broader traffic-safety products.

2.1.3 Practical quick specification checklist for public administration purchasing departments

When comparing vendors and products (especially separators and bollards), special attention should be paid to:

1. impact behaviour (flexible vs rigid), replaceable parts
2. anchoring type (bolt-down, embedded, base plate, glued), utilities conflicts
3. reflective/illumination options
4. modular compatibility (corners, tapers, end pieces, drainage gaps)
5. maintenance and winter service compatibility (snowplows, sweeping)

2.1.4 Market-oriented list of materials used in cycling path furniture

Below is a market-oriented list of materials used in cycling path furniture, grouped by category and typical applications like for bollards, lane separators, kerbs, bike racks, barriers, shelters, benches, signage supports, etc.

2.1.4.1 *Plastics & Polymers*

1. Polyethylene (PE – HDPE / LDPE)
    a. Flexible bollards
    b. Modular lane separators
    c. Cable-protected kerb units
    d. Recycled-plastic benches

Why used: impact resistance, UV stability, lightweight, corrosion-proof

2. Polypropylene (PP)
    a. Modular traffic separators
    b. Base elements for reflective posts

Why used: fatigue resistance, chemical resistance

3. Polyurethane (PU)
    a. Flexible delineator posts
    b. Impact-absorbing separator elements

Why used: high elasticity, returns to shape after impact

4. PVC (Polyvinyl Chloride)
    a. Reflective sleeves
    b. Sign housings

Why used: cost-effective, weather resistant

5. Recycled Mixed Plastics
    a. Lane dividers
    b. Raised cycle track kerbs
    c. Planters / benches

Why used: sustainability goals, durability, low maintenance

2.1.4.2 *Rubber & Elastomers*

1. Recycled Rubber (SBR)
    a. Bolt-down lane separators
    b. Speed cushions
    c. Impact bases for bollards

Why used: shock absorption, skid resistance

2. EPDM Rubber
    a. Colored safety surfacing
    b. Protective edging

Why used: UV resistance, weather durability

3. Thermoplastic Elastomers (TPE)
    a. Flexible separator modules
    b. Anti-slip surfaces

2.1.4.3 *Metals*

1. Carbon Steel (Galvanized / Powder-Coated)
    a. Bollards
    b. Bike racks
    c. Guardrails
    d. Barriers

Why used: strength, structural performance

2. Stainless Steel (AISI 304 / 316)
    a. Premium bollards
    b. Bike stands
    c. Coastal installations

Why used: corrosion resistance

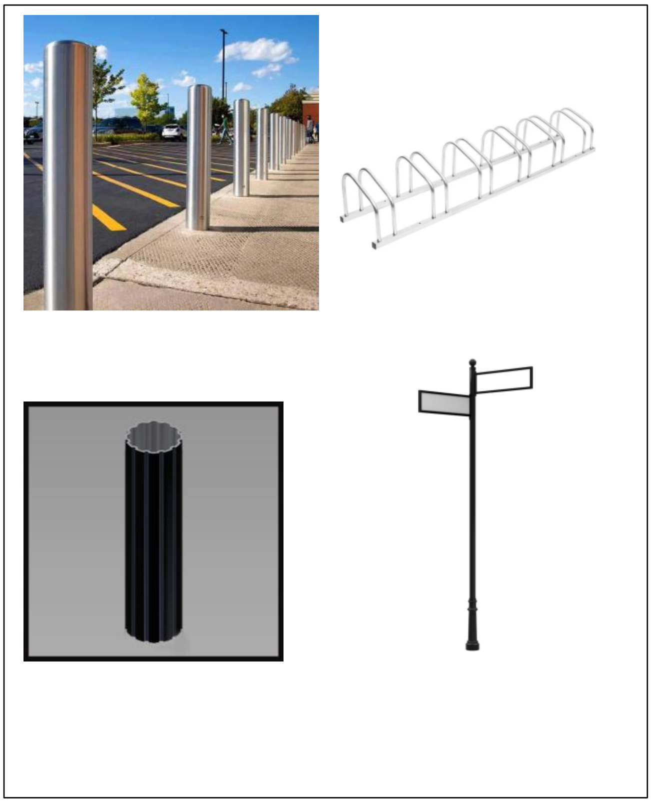
3. Aluminum
    a. Sign poles
    b. Lightweight bollards
    c. Shelter structures

Why used: lightweight, corrosion-resistant

4. Cast Iron
    a. Decorative bollards
    b. Heritage areas

Why used: durability, traditional aesthetics

5. Weathering Steel (Corten)
    a. Architectural separators
    b. Planters along cycle paths



2.1.4.4 *Concrete & Mineral-Based Materials*

1. Reinforced Concrete (Precast)
    a. Fixed bollards
    b. Raised cycle-track kerbs
    c. Traffic islands

Why used: mass, anti-ram resistance, durability

2. Polymer Concrete
    a. Modular separators
    b. Drainage-integrated units

Why used: higher strength-to-weight ratio

3. Fiber-Reinforced Concrete (GFRC)
    a. Lightweight architectural elements
4. Natural Stone (Granite / Limestone)
    a. Historic city bollards
    b. Kerb stones

2.1.4.5 *Wood & Engineered Timber*

1. Hardwood (Oak, Robinia, Tropical Hardwoods)
    a. Natural bollards

    b. Edge barriers
    c. Benches

Why used: aesthetic integration in parks/greenways

2. Softwood (Pressure Treated Pine)
    a. Rural path edging
    b. Rail barriers
3. Glulam / Engineered Timber
    a. Bike shelters
    b. Covered rest areas

2.1.4.6 Composites & Advanced Materials

1. Fiberglass (GFRP / FRP)
    a. Lightweight flexible bollards
    b. Corrosion-free posts
2. Carbon Fiber (rare, premium use)
    a. Lightweight structural elements
3. Wood-Plastic Composite (WPC)
    a. Benches
    b. Decking along cycle paths

2.1.4.7 Surface & Coating Materials (Functional Layers)

1. Powder Coatings (Polyester / Epoxy)
    a. Steel bollards & racks
2. Reflective Films (Microprismatic / Glass Bead)
    a. Delineators
    b. Bollard sleeves
3. Thermoplastic Road Marking Material
    a. Integrated separators with marking
4. Anti-graffiti Coatings
    a. Urban metal/concrete furniture

2.1.4.8 Anchoring & Internal Structural Materials

1. Reinforcing steel bars (rebar)
2. Anchor bolts (stainless / galvanized)
3. Chemical anchors (epoxy resin)
4. Concrete foundations

2.1.5 Material selection guide for cycling infrastructure

2.1.5.1 Urban center (dense city streets)

The key design priorities for dense city streets are:

1. High pedestrian interaction
2. Strong visual quality / architectural integration
3. Resistance to vandalism and frequent impacts
4. Long service life with minimal maintenance

Therefore, recommended materials include:

Element	Preferred Materials	Why
Bollards	Stainless steel, cast iron, powder-coated steel	Durable, aesthetic, vandal resistant
Lane separators	Recycled plastic (HDPE), polyurethane, modular rubber	Visible, impact-tolerant, easy replacement
Bike racks	Stainless steel, galvanized steel	High durability and corrosion resistance
Barriers	Powder-coated steel, aluminum	Structural strength with design flexibility
Planters / benches	Concrete, hardwood, WPC	Urban design integration

It is important to avoid:
1. Untreated wood
2. Low-quality plastics (UV degradation)

2.1.5.2 Highway-adjacent cycle paths

The key design priorities for highway-adjacent cycle paths are:
1. Vehicle impact resistance
2. High visibility and safety
3. Long-term durability
4. Weather resistance

Therefore, recommended materials include:

Element	Preferred Materials	Why
Lane barriers	Reinforced concrete, steel guardrails	High containment strength
Bollards	Flexible polyurethane, fiberglass	Survive vehicle impacts
Separators	Recycled rubber, polymer concrete	Durable and shock absorbing
Sign poles	Aluminum or galvanized steel	Corrosion resistant
Reflective elements	Microprismatic reflective polymers	High nighttime visibility

It is important to avoid:
1. Decorative materials
2. Lightweight furniture not designed for impact

2.1.5.3 Greenways, parks and recreational trails

The key design priorities for greenways, parks and recreational trails are:
1. Natural landscape integration
2. Low visual impact
3. Sustainable materials
4. Moderate durability

Therefore, recommended materials include:

Element	Preferred Materials	Why
Bollards	Hardwood (oak, robinia), timber posts	Natural appearance
Edge barriers	Timber rails, corten steel	Landscape compatibility
Seating	Hardwood, WPC, stone	Comfortable and durable
Bike racks	Powder-coated steel, timber-steel hybrids	Balanced aesthetics
Signage posts	Timber, corten steel	Natural look

It is important to avoid:
1. Bright plastic separators
2. Heavy industrial-looking barriers

2.1.5.4 Temporary and pop-up cycling lanes

The key design priorities for temporary and pop-up cycling lanes are:
1. Fast installation
2. Low cost
3. Easy relocation
4. Minimal ground works

Therefore, recommended materials include:

Element	Preferred Materials	Why
Flexible bollards	Polyurethane or polyethylene	Quick bolt-down installation
Lane separators	Recycled rubber or HDPE modular units	Reusable and lightweight
Temporary barriers	Water-filled plastic barriers	Fast deployment
Sign bases	Recycled rubber	Portable

It is important to avoid:
1. Concrete foundations
2. Heavy steel structures

2.1.6 Summary by performance goal within the context of the SMILE CITY project

The Table 1 below summarize the market-oriented list of materials used in cycling path furniture and combines them with the list of performance goals the public administration technicians might have when planning cycling paths and city spaces. The column "SMILE CITY specific contribution" illustrates material compositions combining ELT's derived recycled materials with actual virgin materials being used traditionally in manufacturing of cycling infrastructure. This sets the context of SMILE CITY project and objective of investigations.

Table 1 Summary by performance goal within the context of the SMILE CITY project. Fields marked green illustrate the interest area of the SMILE CITY project

Performance Goal	Typical Materials	SMILE CITY specific contribution
Flexible impact absorption	PU, PE, rubber	1. PE/PP/HDPE & ELT powder 2. Rubber & devulcanised ELT rubber 3. Rubber & ELT textile fibres 4. PE/PP/HDPE & ELT textile fibres 5. PU glue & ELT crumb (cold and hot molded)
Heavy vehicle protection	Reinforced concrete, steel	
Coastal corrosion resistance	Stainless steel, aluminum, FRP	
Sustainable / recycled	Recycled plastics, rubber, WPC	1. PE/PP/HDPE & ELT powder 2. Rubber & devulcanised ELT rubber 3. Rubber & ELT textile fibres 4. PE/PP/HDPE & ELT textile fibres 5. PU glue & ELT crumb (cold and hot molded)
Natural / park environments	Hardwood, glulam, corten	

This project has received funding from the European Union's Horizon Programme (HORIZON-CL6-2023-CIRCBIO-02) under grant agreement No 101135406

2.2 Commentary on mechanical requirements for materials used in urban furniture production

European standards for cycling infrastructure (bollards, delineators, separators, kerbs, etc.) generally **do NOT** prescribe explicit material-level values such as minimum tensile strength or elongation at break for plastics or rubber.

Instead, they require performance-based mechanical behaviour, verified through product-level tests (impact, deflection, durability).

Manufacturers of cycling path safety elements report that commonly used materials, such as PU-moulded crumb rubber components, typically exhibit tensile strengths of approximately 2 MPa.

In practice, this reveals a significant disparity between the minimum required tensile strength for rubber or thermoplastic materials—generally around 2 MPa—and the substantially higher tensile strengths of virgin rubber compounds or thermoplastics, which often exceed 20 MPa.

This performance gap provides considerable opportunity for the incorporation of recycled materials, even in cases where their inclusion within rubber or polymer matrices leads to some reduction in the mechanical properties of the virgin materials.

European standards f.ex. EN 12899-3 (delineators) defines performance classes, not material properties.

It requires:

1. Impact resistance (pendulum / vehicle tests)
2. Deflection limits (WL classes)
3. No permanent deformation >5% after impact

It defines and includes:

1. Static and dynamic mechanical tests
2. Weathering durability
3. Corrosion resistance

The standard focuses on “performance requirements and test methods” rather than prescribing material composition or mechanical constants.

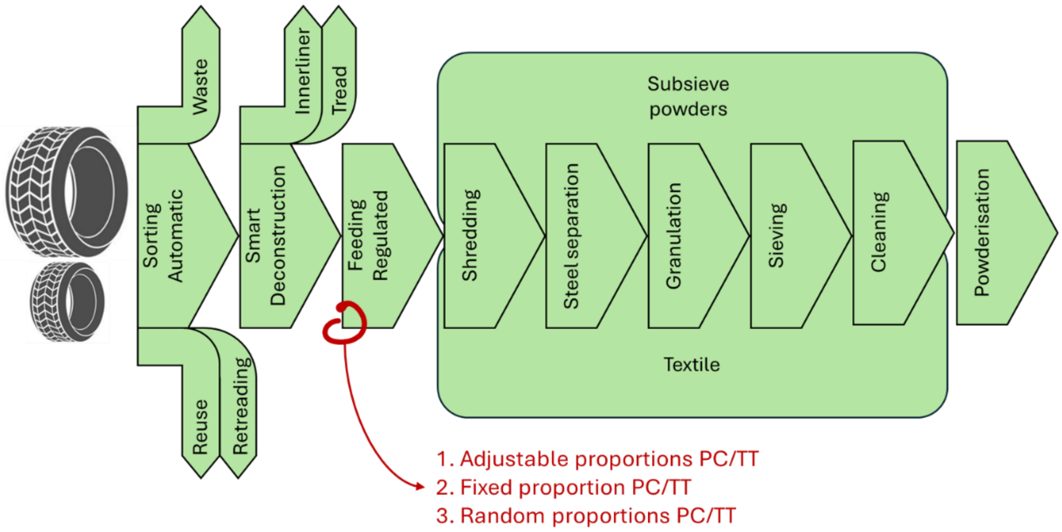
Therefore, required impact resistance or deflection limits are achieved by applying suitable material thickness and shape rather than just material mechanical properties.

2.3 Characterisation of ELT derived eco-friendly materials used in production of urban furniture products

2.3.1 The vision of MTR system

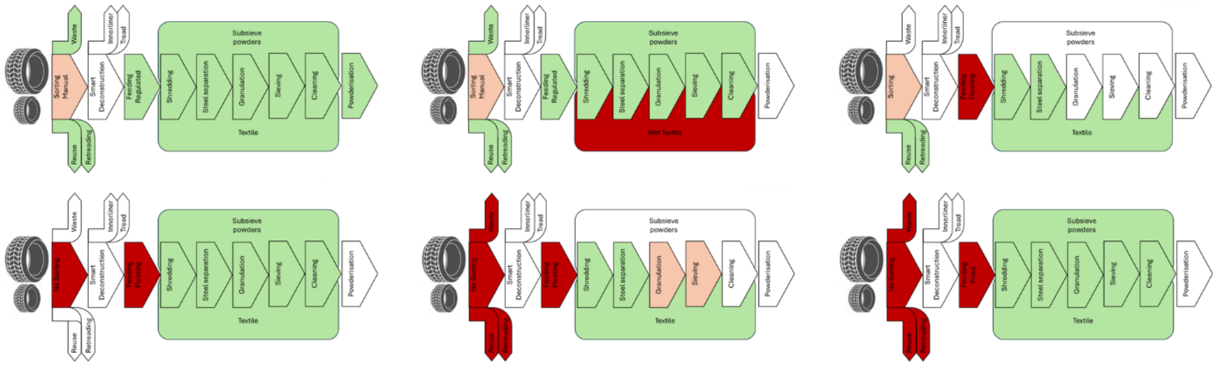
Mechanical Recycling of Tyres (MTR) provides access to ELT-derived materials such as crumb rubber, rubber powders, and textile fibres. These constitute the primary recycled fractions that can be incorporated into thermoplastic and elastomeric matrices for the production of urban furniture components.

The figure below presents a schematic representation of a multi-stage ELT granulation process, illustrating the progressive size reduction and separation of key material streams, including crumb rubber, fine rubber powders, and textile fractions.



1. Adjustable proportions PC/TT
2. Fixed proportion PC/TT
3. Random proportions PC/TT

The figure below presents the actual state of play in various recycling companies across Europe.



2.3.2 Mechanical Recycling of ELTs – Process Considerations

2.3.2.1 Tyre sorting

Sorting of end-of-life tyres (ELTs) is not widely implemented and, where applied, is typically performed manually. However, it is increasingly recommended due to the growing demand for **homogeneous secondary raw materials**.

Sorting may be carried out based on:

1. tyre type (passenger car, truck, off-the-road – OTR),
2. specific models or manufacturers,
3. seasonal categories (summer, winter, all-season).

These categories significantly influence the **chemical composition and material properties** of the recovered rubber. For example, truck tyre treads generally contain a higher proportion of **natural rubber**, which affects elasticity, durability, and processing behaviour.

Recently, **automated sorting systems** have emerged on the market, improving feedstock consistency and enabling more controlled material streams.

2.3.2.2 Tyre deconstruction

Tyre deconstruction is increasingly recognized by the industry as a valuable method for recovering **chemically and mechanically distinct rubber fractions**.

This process enables the separation of:

1. tread rubber,
2. inner liner (butyl rubber),
3. carcass and sidewall materials.

Each of these components exhibits **different mechanical properties and chemical compositions**, making deconstruction particularly relevant for applications requiring **material-specific performance**, such as devulcanization or high-quality recycled compounds.

2.3.2.3 *Feeding strategies in granulation processes*

The feeding of tyres into granulation lines is typically carried out using one of the following approaches:

1. **Fixed Proportions –** tyres are introduced in predetermined ratios, often dictated by process or equipment constraints (e.g. flat-die granulators). A common ratio is approximately **75:25 (truck tyres to passenger car tyres)**. While operationally stable, this approach limits flexibility, particularly when the passenger/truck tyre ratio significantly affects the properties of the final product, such as **rubber-modified asphalt (RMA)**.
2. **Random Proportions –** no control mechanism is applied to regulate the ratio of tyre types. The composition of the feedstock depends on availability and handling logistics. This approach is common in existing installations but may result in **inconsistent product quality**. Improving control typically requires **modifications to the process layout and additional investment**.
3. **Adjustable Proportions –** advanced systems allow controlled dosing of different tyre types, enabling regulation of the **passenger car / truck tyre (PC/TT) ratio**. This approach provides greater flexibility and supports the production of materials with **tailored properties**, which is particularly important for applications such as:
    a. regenerated or devulcanized rubber,
    b. rubber-modified asphalt (RMA),
    c. engineered rubber composites.

2.3.2.4 *Textile separation*

Textile fibres are removed throughout the granulation process using **pneumatic aspiration systems** integrated at multiple stages, including:

1. primary and secondary granulation,
2. sieving,
3. classification.

Efficient textile removal is essential to ensure **product purity and consistency**, particularly for fine rubber fractions.

2.3.2.5 *Recovery of fine fractions (subsieve powders)*

Fine rubber particles (subsieve fractions) are generated during all stages of granulation and classification. These materials are typically characterized by:

- low surface area,
- elevated contamination levels (textiles, steel residues, mineral particles).

Due to their variable purity, special consideration must be given when selecting **end-use applications**, particularly those requiring **consistent material quality and performance**.

2.3.2.6 *Powderisation*

Powderisation is a dedicated process step involving the further size reduction of **clean crumb rubber**, typically from **1–3 mm down to below 0.8 mm**.

This stage is usually performed using:

1. fine grinding systems,
2. cryogenic or ambient milling technologies.

The resulting fine powders are suitable for applications requiring:

1. improved dispersion,
2. high surface reactivity,
3. compatibility with binders (e.g. bitumen, rubber or polymers).

2.3.2.7 *Summary*

The mechanical recycling of ELTs is highly dependent on:

1. feedstock preparation (sorting and deconstruction),
2. process control (feeding strategies),
3. separation efficiency (textile and contaminant removal),
4. and final comminution stages (powderisation).

Optimizing these factors is essential for producing **high-quality, application-specific recycled rubber materials**.

2.3.3 Recycled ELT derived materials – Summary

Parameter	Crumb Rubber	Rubber Powder	Textile Fibres
Particle size	0.8–10 mm	0.05–0.8 mm	1–20 mm (length)
Production method	Ambient / cryogenic grinding	Cryogenic / fine milling	Mechanical + air separation
Bulk density	Approx. 600kg/m^3	Approx. 600kg/m^3	Loose 90kg/m^3 Pelletized 450kg/m^3
Purity	98–99%	>99%	90–98%
Main composition	NR, SBR, carbon black	Same as crumb rubber	PET, polyamide, aramide, viscose
Key property	Elasticity, shock absorption	High surface area	Lightweight reinforcement

2.4 EPD for ELT derived materials and virgin components

2.4.1 ELT derived materials

ELT derived materials offer a deforestation-free alternative to virgin natural rubber imports, therefore help our partners meet EUDR challenges as well as to achieve their CSRD and net-zero targets through verified, low-emission feedstock.

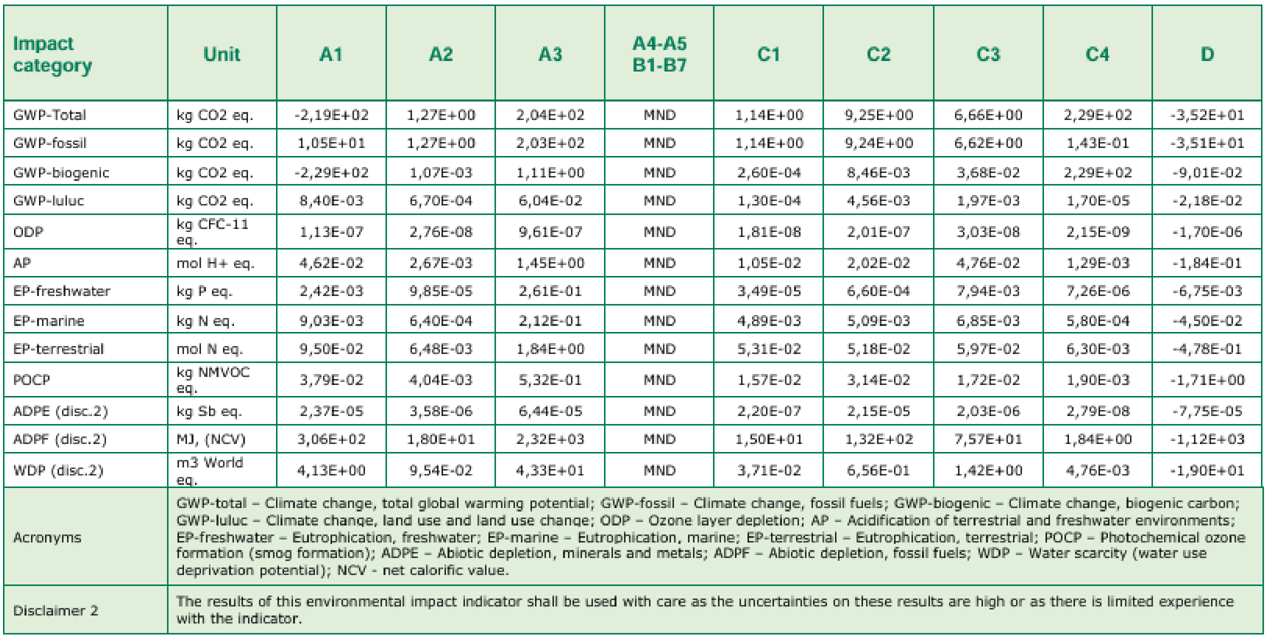
The EPDs for ELT derived rubber powders and textiles were developed according to standard: EN 15804+A2 & ISO 14025 (Third-party verified by Multicert).

The scope of EPDs is a cradle-to-gate with options declaration in accordance with EN 15804+A2:2019, covering the product stage (A1–A3) and end-of-life stages with potential benefits and loads beyond the system boundary (C1–C4 and Module D).

Key findings demonstrate negative values of GWP for ELT derived materials:

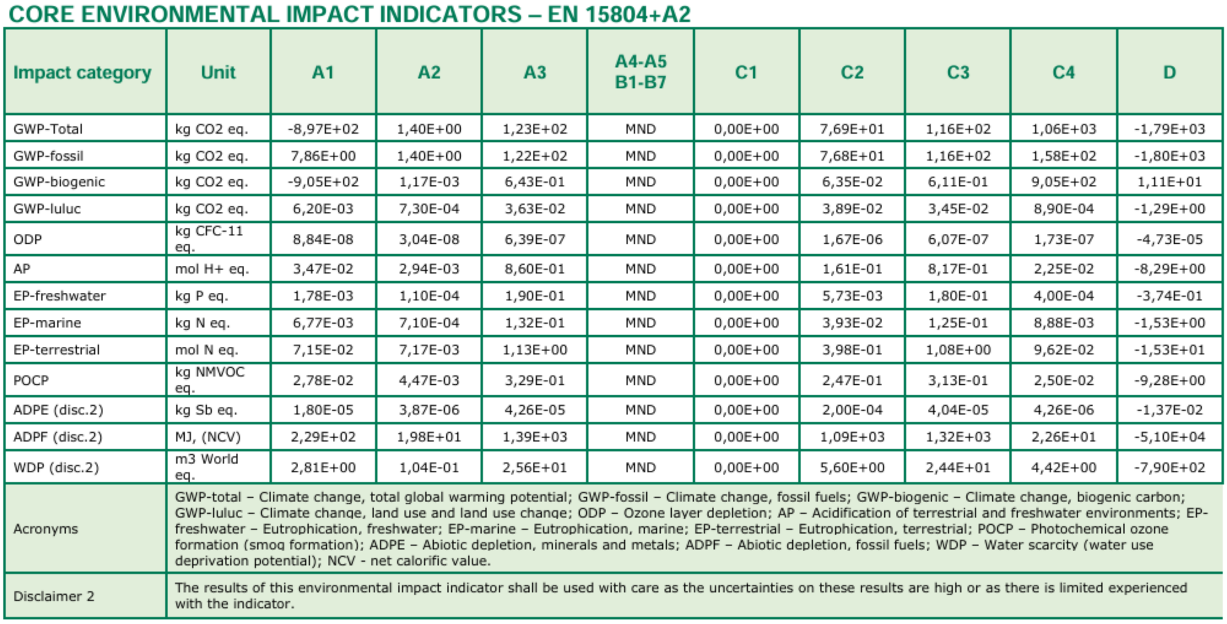
Material	GWP total [kg CO_2-eq/kg]	GWP fossil [kg CO_2-eq/kg]
ELT derived textiles	**(-0,0137)**	**0,214**
ELT derived rubber powder	**(-0,773)**	**0,131**

The below mentioned tables are excerpts from corresponding EPDs prepared for powders and textile materials.



Impact category	Unit	A1	A2	A3	A4-A5 B1-B7	C1	C2	C3	C4	D
GWP-Total	kg CO2 eq.	-2,19E+02	1,27E+00	2,04E+02	MND	1,14E+00	9,25E+00	6,66E+00	2,29E+02	-3,52E+01
GWP-fossil	kg CO2 eq.	1,05E+01	1,27E+00	2,03E+02	MND	1,14E+00	9,24E+00	6,62E+00	1,43E-01	-3,51E+01
GWP-biogenic	kg CO2 eq.	-2,29E+02	1,07E-03	1,11E+00	MND	2,60E-04	8,46E-03	3,68E-02	2,29E+02	-9,01E-02
GWP-luluc	kg CO2 eq.	8,40E-03	6,70E-04	6,04E-02	MND	1,30E-04	4,56E-03	1,97E-03	1,70E-05	-2,18E-02
ODP	kg CFC-11 eq.	1,13E-07	2,76E-08	9,61E-07	MND	1,81E-08	2,01E-07	3,03E-08	2,15E-09	-1,70E-06
AP	mol H+ eq.	4,62E-02	2,67E-03	1,45E+00	MND	1,05E-02	2,02E-02	4,76E-02	1,29E-03	-1,84E-01
EP-freshwater	kg P eq.	2,42E-03	9,85E-05	2,61E-01	MND	3,49E-05	6,60E-04	7,94E-03	7,26E-06	-6,75E-03
EP-marine	kg N eq.	9,03E-03	6,40E-04	2,12E-01	MND	4,89E-03	5,09E-03	6,85E-03	5,80E-04	-4,50E-02
EP-terrestrial	mol N eq.	9,50E-02	6,48E-03	1,84E+00	MND	5,31E-02	5,18E-02	5,97E-02	6,30E-03	-4,78E-01
POCP	kg NMVOC eq.	3,79E-02	4,04E-03	5,32E-01	MND	1,57E-02	3,14E-02	1,72E-02	1,90E-03	-1,71E+00
ADPE (disc.2)	kg Sb eq.	2,37E-05	3,58E-06	6,44E-05	MND	2,20E-07	2,15E-05	2,03E-06	2,79E-08	-7,75E-05
ADPF (disc.2)	MJ, (NCV)	3,06E+02	1,80E+01	2,32E+03	MND	1,50E+01	1,32E+02	7,57E+01	1,84E+00	-1,12E+03
WDP (disc.2)	m3 World eq.	4,13E+00	9,54E-02	4,33E+01	MND	3,71E-02	6,56E-01	1,42E+00	4,76E-03	-1,90E+01
Acronyms	GWP-total – Climate change, total global warming potential; GWP-fossil – Climate change, fossil fuels; GWP-biogenic – Climate change, biogenic carbon; GWP-luluc – Climate change, land use and land use change; ODP – Ozone layer depletion; AP – Acidification of terrestrial and freshwater environments; EP-freshwater – Eutrophication, freshwater; EP-marine – Eutrophication, marine; EP-terrestrial – Eutrophication, terrestrial; POCP – Photochemical ozone formation (smog formation); ADPE – Abiotic depletion, minerals and metals; ADPF – Abiotic depletion, fossil fuels; WDP – Water scarcity (water use deprivation potential); NCV - net calorific value.									
Disclaimer 2	The results of this environmental impact indicator shall be used with care as the uncertainties on these results are high or as there is limited experience with the indicator.									

Table 2 EPD for textiles. Source: Environmental Product Declaration (EPD) verified by Multicert according to EN 15804+A2 and ISO 14025



CORE ENVIRONMENTAL IMPACT INDICATORS – EN 15804+A2

Impact category	Unit	A1	A2	A3	A4-A5 B1-B7	C1	C2	C3	C4	D
GWP-Total	kg CO2 eq.	-8,97E+02	1,40E+00	1,23E+02	MND	0,00E+00	7,69E+01	1,16E+02	1,06E+03	-1,79E+03
GWP-fossil	kg CO2 eq.	7,86E+00	1,40E+00	1,22E+02	MND	0,00E+00	7,68E+01	1,16E+02	1,58E+02	-1,80E+03
GWP-biogenic	kg CO2 eq.	-9,05E+02	1,17E-03	6,43E-01	MND	0,00E+00	6,35E-02	6,11E-01	9,05E+02	1,11E+01
GWP-luluc	kg CO2 eq.	6,20E-03	7,30E-04	3,63E-02	MND	0,00E+00	3,89E-02	3,45E-02	8,90E-04	-1,29E+00
ODP	kg CFC-11 eq.	8,84E-08	3,04E-08	6,39E-07	MND	0,00E+00	1,67E-06	6,07E-07	1,73E-07	-4,73E-05
AP	mol H+ eq.	3,47E-02	2,94E-03	8,60E-01	MND	0,00E+00	1,61E-01	8,17E-01	2,25E-02	-8,29E+00
EP-freshwater	kg P eq.	1,78E-03	1,10E-04	1,90E-01	MND	0,00E+00	5,73E-03	1,80E-01	4,00E-04	-3,74E-01
EP-marine	kg N eq.	6,77E-03	7,10E-04	1,32E-01	MND	0,00E+00	3,93E-02	1,25E-01	8,88E-03	-1,53E+00
EP-terrestrial	mol N eq.	7,15E-02	7,17E-03	1,13E+00	MND	0,00E+00	3,98E-01	1,08E+00	9,62E-02	-1,53E+01
POCP	kg NMVOC eq.	2,78E-02	4,47E-03	3,29E-01	MND	0,00E+00	2,47E-01	3,13E-01	2,50E-02	-9,28E+00
ADPE (disc.2)	kg Sb eq.	1,80E-05	3,87E-06	4,26E-05	MND	0,00E+00	2,00E-04	4,04E-05	4,26E-06	-1,37E-02
ADPF (disc.2)	MJ, (NCV)	2,29E+02	1,98E+01	1,39E+03	MND	0,00E+00	1,09E+03	1,32E+03	2,26E+01	-5,10E+04
WDP (disc.2)	m3 World eq.	2,81E+00	1,04E-01	2,56E+01	MND	0,00E+00	5,60E+00	2,44E+01	4,42E+00	-7,90E+02
Acronyms	GWP-total – Climate change, total global warming potential; GWP-fossil – Climate change, fossil fuels; GWP-biogenic – Climate change, biogenic carbon; GWP-luluc – Climate change, land use and land use change; ODP – Ozone layer depletion; AP – Acidification of terrestrial and freshwater environments; EP-freshwater – Eutrophication, freshwater; EP-marine – Eutrophication, marine; EP-terrestrial – Eutrophication, terrestrial; POCP – Photochemical ozone formation (smog formation); ADPE – Abiotic depletion, minerals and metals; ADPF – Abiotic depletion, fossil fuels; WDP – Water scarcity (water use deprivation potential); NCV - net calorific value.									
Disclaimer 2	The results of this environmental impact indicator shall be used with care as the uncertainties on these results are high or as there is limited experienced with the indicator.									

Table 3 EPD for powders. Source: Environmental Product Declaration (EPD) verified by Multicert according to EN 15804+A2 and ISO 14025

2.4.2 GWP comparison with virgin materials

Category	Material	GWP total [kg CO_2-eq/kg]	GWP fossil [kg CO_2-eq/kg]	Reference
Virgin components	**Natural Rubber (NR)**	2.0 – 3.0	0.7 – 1.5	ecoinvent / FAO
	Synthetic Rubber (SBR)	2.7 – 3.8	2.6 – 3.7	PlasticsEurope / IISRP

This project has received funding from the European Union's Horizon Programme (HORIZON-CL6-2023-CIRCBIO-02) under grant agreement No 101135406

	Carbon Black (Virgin)	2.4 – 3.2	2.4 – 3.2	ICBA / ecoinvent
	rCB (ELT, pyrolytic)	0.7 – 1.4	0.7 – 1.3	BlackCycle / LCA Pilot
	Polypropylene (PP)	1.7 – 2.2	1.7 – 2.2	PlasticsEurope Eco-profile
	PE / HDPE / LDPE	1.8 – 2.5	1.8 – 2.5	PlasticsEurope Eco-profile
	EVA	2.8 – 3.5	2.8 – 3.5	Idemat / PlasticsEurope
	Polyurethane (PU)	2.5 – 3.5	2.5 – 3.5	ISOPA / PlasticsEurope
ELT derived materials	**ELT derived textiles**	**(-0,0137)**	**0,214**	EN 15804+A2 & ISO 14025 (Third-party verified by Multicert)
	ELT derived rubber powder	**(-0,773)**	**0,131**	EN 15804+A2 & ISO 14025 (Third-party verified by Multicert)

2.5 Experimental work results

2.5.1 Summary of experimental works results

Vulcanised rubbers and textiles recovered from ELTs can be reprocessed and used in a circular way using following methods:

1. Reactive sintering
2. Devulcanisation/reclaiming
3. Rubber compounding
4. Melt-blending

Methods are shortly characterised as follows:

1. Reactive Sintering

Reactive sintering is a **direct recycling method of ground tyre rubber (GTR)** in which rubber particles are subjected to **elevated temperature and pressure**, leading to the formation of free radicals that promote **simultaneous devulcanization/degradation and secondary cross-linking**, resulting in a consolidated rubber material. Polyurethane binder could be used as a promotor of adhesion.

This process enables the production of materials composed entirely of GTR without the need for additional matrices.

2. Reclaiming and Devulcanisation

Reclaiming and devulcanisation refer to processes involving the **partial breakdown of the cross-linked rubber network** through the cleavage of sulfur cross-links and, in some cases, polymer chains.

These processes aim to:

- improve the **flowability and processability** of GTR,
- enable further processing into new materials,
- enhance compatibility with other polymers or additives.

They are typically associated with **chemical, thermal, or mechanical treatments** that modify the structure of vulcanized rubber.

3. Rubber Compounding

Rubber compounding is the process of **formulating GTR with elastomers, curing systems, and additives** to produce new rubber materials with tailored properties.

This involves:

- blending GTR with virgin or recycled elastomers,
- incorporation of curing agents and modifiers,
- subsequent shaping and vulcanization.

The goal is to obtain materials with **improved mechanical performance and controlled properties** suitable for engineering applications.

4. Melt-Blending

Melt-blending is a recycling technique in which GTR is **mixed with thermoplastic polymers under high-temperature shear conditions**, typically using internal mixers or extrusion processes.

The process involves:

- heating thermoplastics above their melting temperature,
- dispersing GTR particles within the polymer matrix,
- shaping via compression or injection molding.

This method produces **thermoplastic elastomer-like composites** combining the elasticity of rubber with the processability of thermoplastics.

The following tables summarize both the findings of SMILE CITY study and global experience in the reprocessing of vulcanised rubber and textile fractions recovered from ELTs. Existing studies predominantly address high loading levels of recycled materials, generally above 70% by weight. In contrast, SMILE CITY study expands the analysis to include lower loading ratios (below 50% by weight), with a particular focus on determining optimal and industrially viable compositions.

Table 4 Reactive sintering

Recycling technology	**Sample composition**	**Recycled content**	**Mechanical properties**		
			Tensile strength (MPa)	Elongation at brake (%)	Charpy V-notch (kJ/m^2)
Reactive sintering	Crumb <3.5 mm without any additives	100%	0.6-1.1	22-84	
	Crumb 2-3 mm + polyurethane binder (up to 30 wt%)	>70%	0.4-1.2	3-62	
	Powder 0.18-0.38 mm + sulfur-based curing system	~100%	6.7-9.5	160-240	

Reactive sintering is predominantly applied to coarse rubber crumb and is widely utilized in applications involving polyurethane binders. According to manufacturers' data, tensile strength values in the range of 0.4–1.2 MPa, as presented in the table above, are considered suitable for the production of urban cycling infrastructure components.

Table 5 Reclaiming and devulcanisation

Recycling technology	**Sample composition**	**Recycled content**	**Mechanical properties**		
			Tensile strength (MPa)	Elongation at brake (%)	Charpy V-notch (kJ/m^2)
Reclaiming & Devulc.	Reclaimed powder <0,6 mm and molded without additives	100%	3.2-5.1	135-160	

This project has received funding from the European Union's Horizon Programme (HORIZON-CL6-2023-CIRCBIO-02) under grant agreement No 101135406

	Reclaimed powder 0.25 mm + sulfur-based curing system	~100%	4.2-8.1	109-202	
	Reclaimed powder <1.5 mm (mix of tyres) + sulfur-based curing system	~100%	4.1-6.9	187-310	
	Reclaimed powder (whole PC tyre) + sulfur-based curing system	~100%	5-8	<200%	
	Reclaimed powder (TT treads) + sulfur-based curing system	~100%	6.0-16.5	355-400	

Reclaiming and devulcanization processes generally result in superior mechanical performance compared to reactive sintering. These methods are primarily applied to fine rubber powders and devulcanized rubber materials. A clear trend can be observed whereby decreasing particle size leads to improved mechanical properties of the re-vulcanized product. Furthermore, the characteristics of the feedstock material play a critical role: the highest performance is typically achieved using powders derived from truck tyre treads, followed by those obtained from whole passenger tyres, and finally from mixed passenger and truck tyre streams. This observation underscores the importance of effective tyre sorting, as feedstock selection has a direct impact on the mechanical performance of the resulting re-vulcanized materials.

Table 6 Rubber compounding

Recycling technology	**Sample composition**	**Recycled content**	**Mechanical properties**		
			Tensile strength (MPa)	Elongation at brake (%)	Charpy V-notch (kJ/m^2)
Rubber compound.	Devulc + SBR or NR (0-20 wt%) + sulfur-based curing system	>80%	3.1-6.0	100-200	
	Devulc powder <0.595 mm + NR (0-30 wt%) + sulfur-based curing system	>70%	8-9	400-575	
	Devulc powder mix of tires <0.6 mm + elastomers: SEBS, SBR or EOC (2.5-15phr) + peroxide-based curing agent	>70%	5.2-8.1	113-136	
	Textiles + SBR + sulfur-based curing system	5-50%	12-20 (50-83%)	300-650 (41-90%)	

Rubber compounding enables the achievement of higher mechanical performance compared to reactive sintering as well as reclaiming and devulcanization processes. In this approach, a portion of the recycled material is replaced with virgin rubber, resulting in mechanical property retention levels of approximately 50% relative to the virgin material. The results obtained in this study further demonstrate the high loading potential of textile fractions, which can be incorporated without significant deterioration of the mechanical properties of the rubber matrix. This finding supports the classification of textile fibres as a “compatible” or “functional” filler, exhibiting superior performance compared to conventional mineral fillers such as calcium carbonate or talc. Notably, the retention of mechanical properties remains high, reaching levels of 40–90% across a broad loading range of 5–50 wt%.

Table 7 Melt-blending

Recycling technology	**Sample composition**	**Recycled content**	**Mechanical properties**		
			Tensile strength (MPa)	Elongation at brake (%)	Charpy V-notch (kJ/m^2)
Melt-blending	Powder 0.315-0.630 mm + EVA 20-30 wt%	>70%	1.6-2.7	100-140	
	Powder mix of tires <0.6 mm + LLDPE, EOC, TOR, EVA (25 wt%)	75%	2.9-4.4	66-440	
	Powder truck tires + HDPE (20 wt%) + curing agents	80%	2.2-4.3	10-58	
	Powder treads and side walls 0.595 mm + PP (20 wt%) + curing agents	80%	1.5-2.5	15-38	
	Powder 0,4 mm + PP no curing agents	10-30%	18.5-28.2 (54-82%)	12.7-16.7 (2-3%)	**3.3-4.9** **(110-163%)**
	Powder 0,4 mm + HDPE no curing agents	10-30%	15.8-21.8 (63-87%)	34-54.1 (7-12.2%)	**4-6.4** **(108-172%)**
	Powder 0,8 mm + LDPE no curing agents	40%	6,21 (65%)	35 (46%)	

Melt blending of thermoplastic matrices with recycled rubber demonstrates relatively high tensile strength values, accompanied by notably high retention levels in the range of 65–87%. However, in comparison with elastomeric systems, the elongation at break remains moderate. Particularly noteworthy are the results obtained for impact performance, where the Charpy impact resistance increases with increasing content of recycled material in the thermoplastic matrix. This enhancement surpasses the performance of the corresponding virgin polymers and indicates significant practical potential. Consequently, for urban infrastructure components exposed to impact loading, the incorporation of recycled rubber powders into thermoplastic matrices should be strongly considered as their impact resistance could reach 172% of the value of the virgin polymer at the 30% loading ratio of ELT derived rubber powder.

2.5.2 Example of thermoplastic PP and HDPE compounds with rubber powders

Study of thermoplastic PP and HDPE compounds with ELT derived rubber powder (0,4mm) up to the loading ratio 30% wt. were conducted with virgin polymers RESLEN HDPE and PP PGUM produced by Polimarky Poland. No curing agents neither compatibilizers were used.

Table 8 HDPE compounds with rubber powders. Loading ratio from 5% to 30% wt.

No.	**Test Name**	**Standard**	**Base**	**Base**	**Base**	**Base**	**Base**

			Polymer HDPE	Polymer + 5% rubber	Polymer + 10% rubber	Polymer + 20% rubber	Polymer + 30% rubber
1	MFR 230°C / 2.16 kg [g/10 min]	PN-EN ISO 1133	22.8	21.4	17.8	12.2	9.5
2	Transverse shrinkage [%]	PN-EN ISO 2505	2	1.5	1.33	1.33	1.17
3	Longitudinal shrinkage [%]	PN-EN ISO 2505	1.7	1.69	1.67	1.5	1.5
4	Ash content 600°C [%]	PN-EN ISO 3451-1	0	0.9	2	4	7.4
5	Moisture content [%]	In-house method	0.08	0.05	0.01	0.03	0.03
6	Density [g/cm³]	PN-EN ISO 1183	0.96	0.96	0.97	0.99	1.01
7	Tensile strength [MPa]	PN-EN ISO 527	25	24	21.8	18.5	15.8
8	Stress at break [MPa]	PN-EN ISO 527	12.5	12.4	14.7	15.7	14.3
9	Elongation at break [%]	PN-EN ISO 527	440	374	54.1	39	34
10	Yield elongation [%]	PN-EN ISO 527	8.8	9	10	11	11
11	Tensile modulus [MPa]	PN-EN ISO 527	1655	1504	1286	1070	926
12	Charpy impact strength (unnotched) [kJ/m²]	PN-EN ISO 179	4/4 NB	4/4 NB	4/4 NB	4/4 NB	48.3
13	Charpy impact strength (notched) [kJ/m²]	PN-EN ISO 179	3.7	3.8	4	5.2	6.4

Table 9 PP compounds with rubber powders. Loading ratio from 10% to 30% wt.

No.	Test Name	Standard	Base Polymer PP	Base Polymer + 10% rubber	Base Polymer + 20% rubber	Base Polymer + 30% rubber
1	MFR 230°C / 2.16 kg [g/10 min]	PN-EN ISO 1133	23.3	17.9	13.9	11.6
2	Transverse shrinkage [%]	PN-EN ISO 2505	1.5	0.8	1.2	1.2
3	Longitudinal shrinkage [%]	PN-EN ISO 2505	1.5	1.0	0.9	1.2
4	Ash content 600°C [%]	PN-EN ISO 3451-1	0	1.4	4	7.2
5	Moisture content [%]	In-house method	0.07	0.06	0.1	0.07
6	Density [g/cm³]	PN-EN ISO 1183	0.90	0.93	0.96	0.99
7	Tensile strength [MPa]	PN-EN ISO	34.1	28.2	23.1	18.5

		527				
8	Stress at break [MPa]	PN-EN ISO 527	35	27.5	22.7	18
9	Elongation at break [%]	PN-EN ISO 527	480	12.7	15.1	16.7
10	Yield elongation [%]	PN-EN ISO 527	10	7.3	8.3	9.2
11	Tensile modulus [MPa]	PN-EN ISO 527	1712	1718	1374	1198
12	Charpy impact strength (unnotched) [kJ/m²]	PN-EN ISO 179	–	13	18	18.7
13	Charpy impact strength (notched) [kJ/m²]	PN-EN ISO 179	3	3.3	4.4	4.9

2.5.2.1 Key observations

As noted in the previous chapter, particularly noteworthy are the results obtained for impact performance, where the Charpy impact resistance increases with increasing content of recycled material in the thermoplastic matrix. This enhancement surpasses the performance of the corresponding virgin polymers and indicates significant practical potential. Consequently, for urban infrastructure components exposed to impact loading, the incorporation of recycled rubber powders into thermoplastic matrices should be strongly considered as their impact resistance could reach 172% of the value of the virgin polymer at the 30% loading ratio of ELT derived rubber powder.

2.5.2.2 Impact on cost and GWP

Impact on cost
Actual prices of available HDPE / PP are in the range of 1 EUR/kg
Actual prices of available GTR powders (0,8mm) are around 0,16 EUR/kg
Therefore, the cost reduction **ratio is 1:6** whenever GTR powders (ELT derived powders) substitute virgin HDPE or PP.

Impact on GWP
Value of GWP total for ELT derived powders is negative (-0,773) kg CO_2-eq/kg.
In the worst scenario value of GWP fossil for ELT derived powders is 0,131 kg CO_2-eq/kg.
Values of GWP fossil for HDPE or PP are above 1.8 kg CO_2-eq/kg
Therefore, the GWP fossil reduction ratio is in the **range of 1:13** whenever ELT derived powders substitute LDPE in thermoplastic compounds.

2.5.3 Example of thermoplastic LDPE compound with rubber powders

Experiment was conducted in Aimplas laboratories under the SMILE CITY project.

2.5.3.1 Design of experiment

An experimental study has been launched to formulate thermoplastic elastomers (TPEs) through compounding of virgin polyolefins with recycled rubber derived from end-of-life tyres (ELT).
The work was based on the use of two grades of low-density polyethylene (LDPE), each with a different melt flow index (MFI), as the polymeric matrix, and a rubber fraction with controlled particle size (0.8 mm) as the elastomeric filler. The gradual incorporation of rubber (up to 40%) will allow assessment of the influence of recycled content on processability, stability, and mechanical performance of the resulting materials.
The formulations are being processed via compounding using a Coperion ZSK 26 twin-screw extruder, with an optimized temperature profile ranging from 190 to 210 °C, and an underwater pelletizing system. Two K-Tron 20 feeders are used for precise dosing of the components. For each LDPE type, five formulations with

increasing rubber content (0%, 10%, 20%, 30%, and 40%) are being produced.

The study includes the injection moulding of dog-bone specimens for mechanical characterization, as well as an evaluation of the technical feasibility of these formulations for urban applications such as street furniture, shock-absorbing elements, or flexible pavements.

2.5.3.2 Objectives

The main objective of this experimental work is to **develop and evaluate thermoplastic elastomer formulations** based on low-density polyethylene (LDPE) and recycled rubber from end-of-life tyres, processed by compounding extrusion.

To achieve this, the following specific objectives have been defined:

1. **Formulate and compound** a series of LDPE-based materials with increasing rubber content (0%, 10%, 20%, 30%, and 40%) using two different LDPE grades with distinct melt flow indices.
2. **Process all formulations** under controlled and replicable extrusion conditions, optimizing the thermal and mechanical settings to ensure homogeneity and minimize degradation.
3. **Produce injection-moulded specimens** (dog-bone type) from each formulation for mechanical testing, particularly tensile strength and elongation at break.
4. **Assess the influence** of rubber content and LDPE grade on the processability, dispersion, and physical properties of the resulting TPEs.
5. **Generate data** that will support the validation and scaling of the most promising formulations for circular urban applications within the SMILE CITY project.

2.5.3.3 Materials

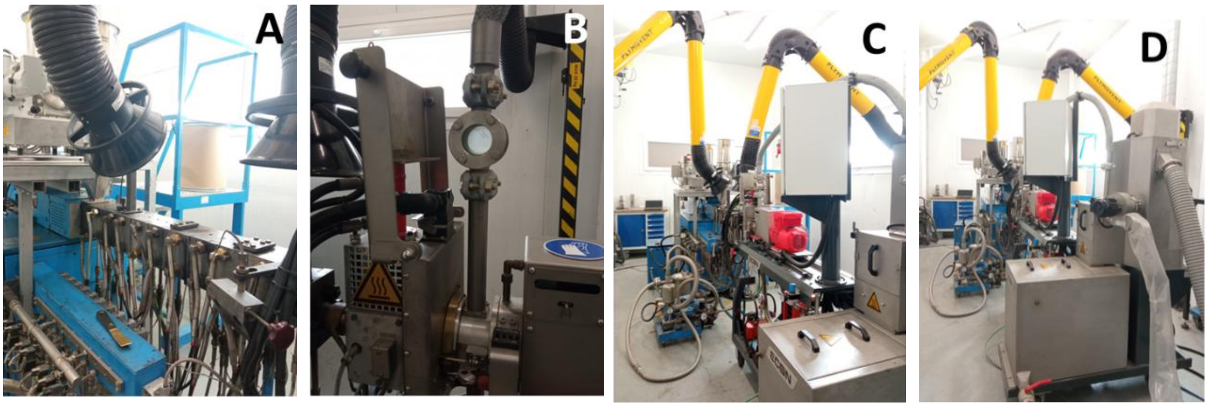
Two different low-density polyethylene (LDPE) grades were selected as polymer matrices:

1. LDPE PURELL PE 3020 K – MFI 4 g/10 min (LyondellBasell)
2. LDPE 310 E – MFI 0.75 g/10 min (DOW)

The elastomeric component was a recycled rubber fraction obtained from ELT, with a particle size of 0.8 mm. No compatibiliser was added at this stage, and all other process variables were kept constant.

2.5.3.4 Equipment and Processing Conditions

All formulations were processed using a Coperion ZSK 26 co-rotating twin-screw extruder, equipped with underwater strand pelletizing and two K-Tron 20 gravimetric feeders.



Fot. 1 A) Coperion twin-screw extruder; B) Pelletizing equipment; C and D) Complete experimental setup.

The following extrusion parameters were applied:

1. Temperature profile: 190 → 210 °C
2. Screw speed: 100 rpm
3. Production rate: 8 kg/h
4. Drying: All formulations were dried for 2 hours at 60 °C prior to injection moulding

2.5.3.5 Formulation Summary

Test run	Sample code	LDPE Grade	LDPE (%)	Rubber (%)	LDPE (kg/h)	Rubber (kg/h)	Total (kg/h)
1	PRO23-0129-05-01	PURELL PE 3020 K	100	0	8.0	0.0	8.0
2	PRO23-0129-05-02	PURELL PE 3020 K	90	10	7.2	0.8	
3	PRO23-0129-05-03	PURELL PE 3020 K	80	20	6.4	1.6	
4	PRO23-0129-05-04	PURELL PE 3020 K	70	30	5.6	2.4	
5	PRO23-0129-05-05	PURELL PE 3020 K	60	40	4.8	3.2	
6	PRO23-0129-06-01	LDPE 310 E	100	0	8.0	0.0	
7	PRO23-0129-06-02	LDPE 310 E	90	10	7.2	0.8	
8	PRO23-0129-06-03	LDPE 310 E	80	20	6.4	1.6	
9	PRO23-0129-06-04	LDPE 310 E	70	30	5.6	2.4	
10	PRO23-0129-06-05	LDPE 310 E	60	40	4.8	3.2	

The compounding of the different LDPE–GTR formulations was successfully carried out using the extrusion process described in the previous section. All formulations were obtained without processing issues, confirming the feasibility of incorporating ground tyre rubber (GTR) into LDPE matrices through conventional melt compounding techniques.

Once the materials were compounded, the resulting pellets were processed by injection moulding to prepare standard specimens for mechanical characterization. Dog-bone specimens (type 1BA) were produced for tensile testing according to the applicable standards.

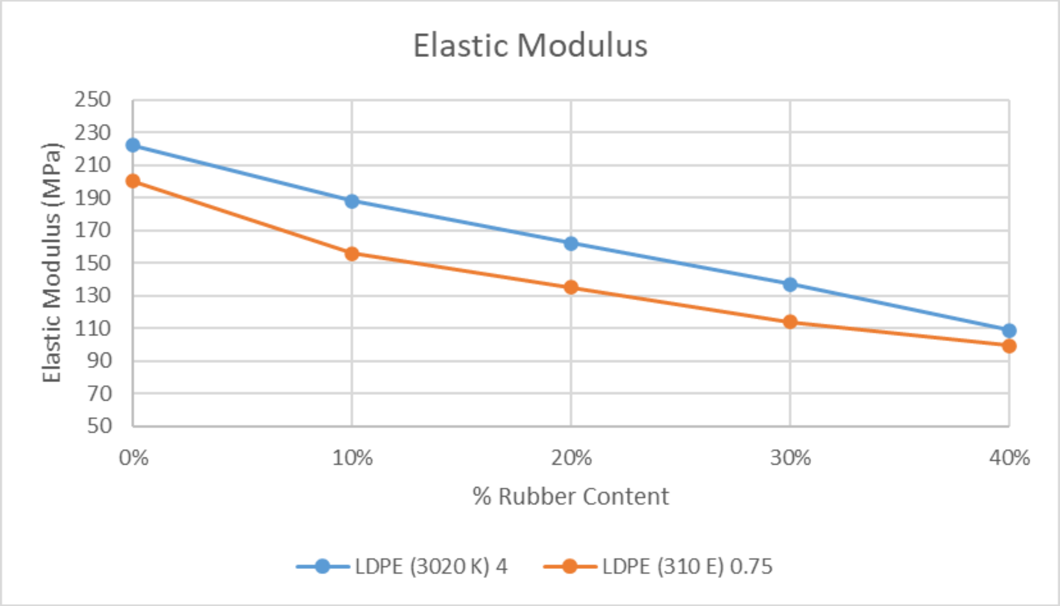
The following formulations were prepared and injected for mechanical characterization:

Test	Sample Code	Description
1	PRO23-0129-05-01	LDPE 3020K (MFI 4)
2	PRO23-0129-05-02	LDPE 3020K + 10% GTR (0.8 mm)
3	PRO23-0129-05-03	LDPE 3020K + 20% GTR (0.8 mm)
4	PRO23-0129-05-04	LDPE 3020K + 30% GTR (0.8 mm)

5	PRO23-0129-05-05	LDPE 3020K + 40% GTR (0.8 mm)
6	PRO23-0129-06-01	LDPE 310E (MFI 0.75)
7	PRO23-0129-06-02	LDPE 310E + 10% GTR (0.8 mm)
8	PRO23-0129-06-03	LDPE 310E + 20% GTR (0.8 mm)
9	PRO23-0129-06-04	LDPE 310E + 30% GTR (0.8 mm)
10	PRO23-0129-06-05	LDPE 310E + 40% GTR (0.8 mm)

These specimens were subsequently used to evaluate the mechanical behaviour of the developed TPE compounds.

2.5.3.6 Mechanical characterization



Graph 1 Elastic modulus of LDPE–GTR compounds as a function of rubber content

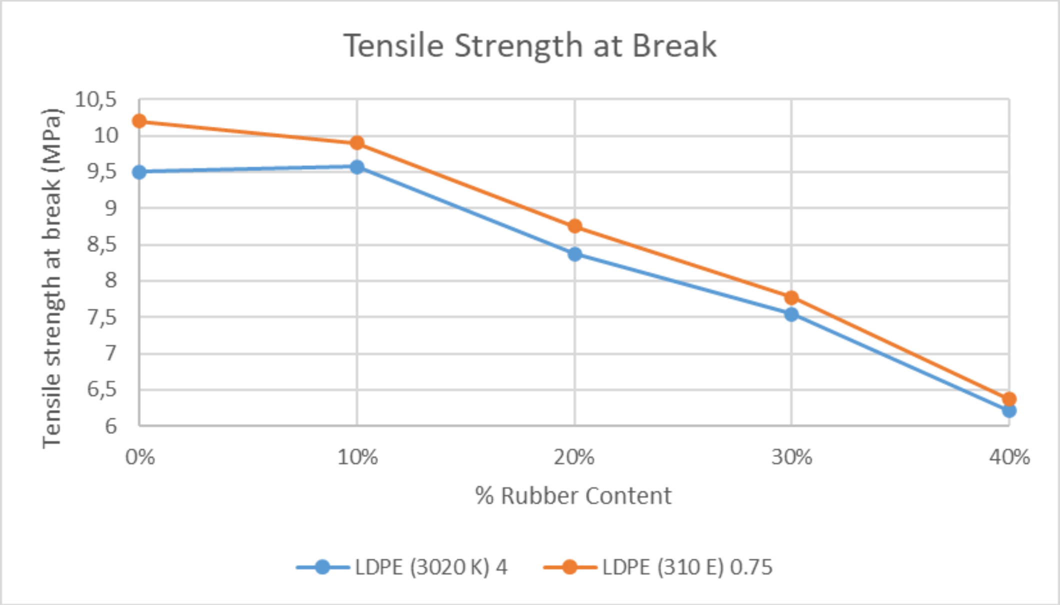
The elastic modulus of the developed LDPE–GTR compounds decreases progressively as the rubber content increases for both LDPE matrices evaluated.

For the LDPE 3020K grade (MFI 4), the elastic modulus decreases from 222 MPa for the neat polymer to 109 MPa when incorporating 40 wt.% GTR. A similar trend is observed for the LDPE 310E grade (MFI 0.75), where the modulus decreases from 200 MPa to approximately 100 MPa for the same rubber content.

This behaviour is expected and is mainly attributed to the incorporation of the elastomeric phase into the thermoplastic matrix. Ground tyre rubber particles present a significantly lower stiffness than the LDPE matrix, and their increasing presence reduces the overall rigidity of the material. As the GTR content increases, the composite behaviour becomes progressively more elastomer-like, leading to a gradual reduction in stiffness.

Additionally, the rubber particles act as dispersed inclusions within the polymer matrix, disrupting the continuity of the thermoplastic phase and reducing the effective load transfer within the material. When comparing both matrices, the LDPE 3020K formulations consistently show slightly higher modulus values than the LDPE 310E formulations at equivalent rubber contents. This behaviour is likely related to the intrinsic characteristics of the polymer grades, particularly their melt flow index and molecular structure, which influence the stiffness of the final compound.

Despite the decrease in stiffness, the obtained modulus values (approximately 100–220 MPa) remain within a range compatible with semi-flexible thermoplastic materials, which may be suitable for applications such as urban paving elements or flexible structural components.



Graph 2 Influence of GTR content on the tensile strength at break of LDPE-based compounds (3020K and 310E).

The tensile strength at break of the LDPE–GTR formulations shows a gradual decrease as the rubber content increases for both LDPE grades evaluated.

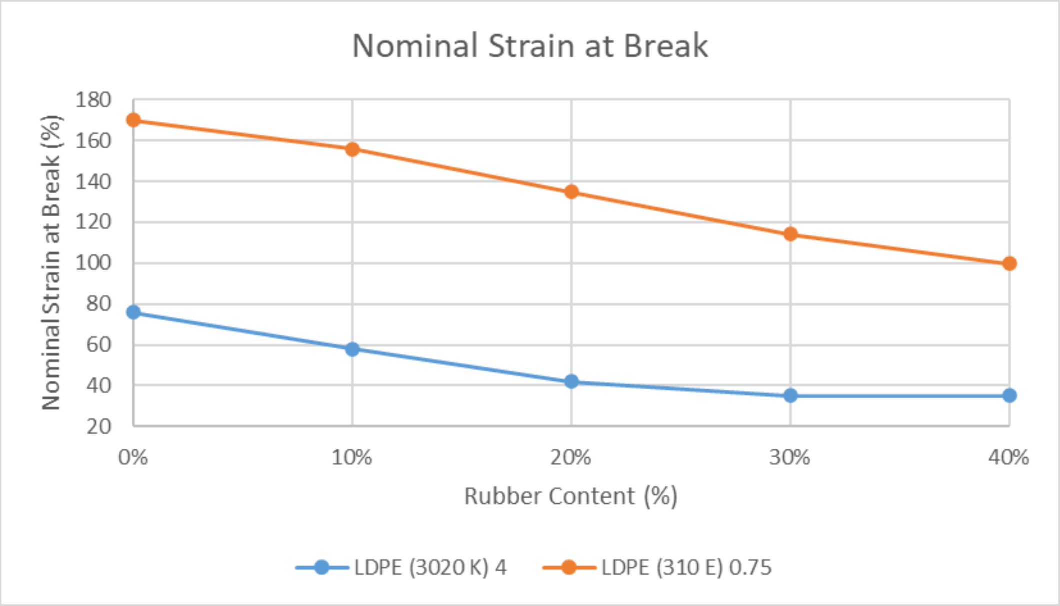
For the LDPE 3020K matrix, the tensile strength decreases from 9.5 MPa for the neat polymer to 6.21 MPa when incorporating 40 wt.% GTR. A similar trend is observed for the LDPE 310E formulations, where the tensile strength decreases from 10.2 MPa to 6.37 MPa over the same range of rubber content.

This reduction in tensile strength is mainly associated with the presence of recycled rubber particles dispersed within the thermoplastic matrix. Since the GTR particles do not form a continuous phase and exhibit limited interfacial adhesion with the LDPE matrix, they can act as stress concentration points during deformation. As the rubber fraction increases, the load transfer within the material becomes less efficient, leading to earlier failure under tensile stress.

Despite this decrease, the reduction in tensile strength remains moderate even at high rubber contents. The formulations containing 40 wt.% GTR still maintain tensile strengths around 6 MPa, indicating that the materials retain acceptable mechanical performance while significantly increasing the recycled content.

When comparing both polymer matrices, the LDPE 310E formulations show slightly higher tensile strength values at low rubber contents. However, the difference between both grades becomes less pronounced as the rubber fraction increases, suggesting that the mechanical behaviour of the blends is increasingly governed by the presence of the elastomeric phase.

Overall, the obtained results confirm that the incorporation of recycled tyre rubber modifies the mechanical behaviour of the LDPE matrix while maintaining mechanical resistance within a range compatible with semi-flexible polymer applications.



Graph 3 Influence of GTR content on the nominal strain at break of LDPE-based compounds (3020K and 310E).

The nominal strain at break of the LDPE–GTR formulations shows a decreasing trend with increasing rubber content for both LDPE matrices. However, the magnitude of this reduction differs significantly between the two polymer grades.

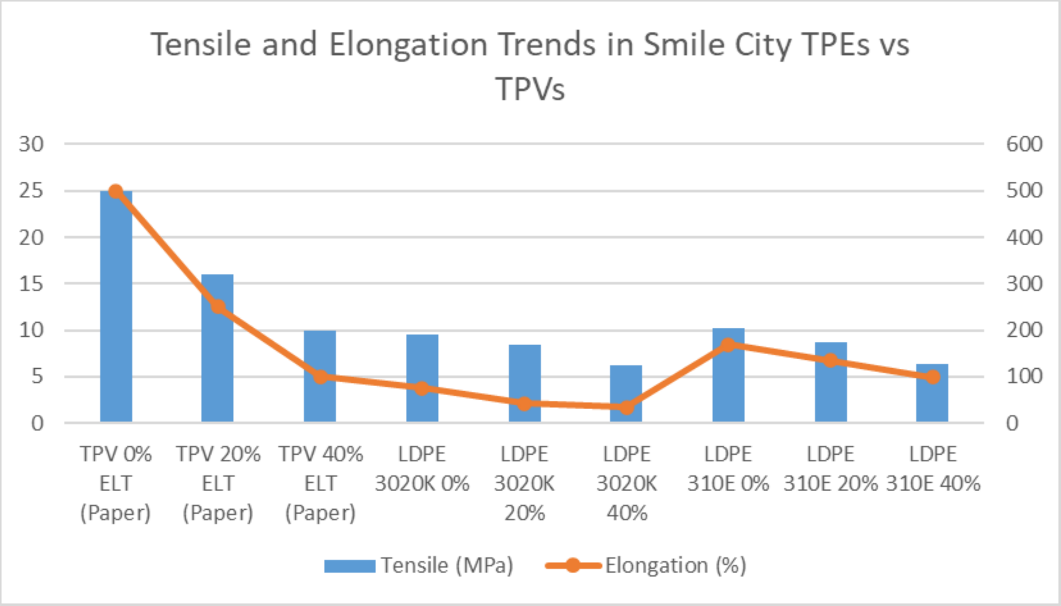
For the LDPE 3020K formulations, the elongation at break decreases from 76 % for the neat polymer to approximately 35 % when the GTR content reaches 40 wt.%. This reduction indicates that the incorporation of rubber particles progressively limits the ability of the material to undergo plastic deformation before failure.

In contrast, the LDPE 310E formulations exhibit considerably higher elongation values across the entire composition range. The neat LDPE 310E presents an elongation at break of 170 %, which decreases gradually to approximately 100 % at 40 wt.% GTR. Despite the addition of a significant amount of recycled rubber, the material retains a relatively high deformability. The observed behaviour can be attributed to the intrinsic characteristics of the polymer matrices. LDPE 310E, with a lower melt flow index (MFI 0.75), is expected to have a higher molecular weight and greater chain entanglement, which typically results in improved ductility and resistance to deformation. As a result, this matrix is better able to accommodate the presence of dispersed rubber particles without a drastic loss of elongation.

Conversely, the LDPE 3020K grade (MFI 4) exhibits a lower initial ductility and is therefore more sensitive to the presence of rigid inclusions such as GTR particles. These particles can act as initiation points for crack propagation during deformation, reducing the elongation at break of the material.

Overall, the results indicate that the choice of polymer matrix plays a key role in preserving the deformability of LDPE–GTR compounds, with the LDPE 310E formulations demonstrating a more favourable balance between recycled content and mechanical flexibility.

This project has received funding from the European Union's Horizon Programme (HORIZON-CL6-2023-CIRCBIO-02) under grant agreement No 101135406



Graph 4 Comparison of tensile strength and elongation at break between TPV systems from literature and LDPE–GTR compounds developed in the SMILE CITY project.

The tensile strength and elongation results obtained for the LDPE–GTR compounds were also compared with values reported in the literature for thermoplastic elastomers containing recycled tyre rubber.

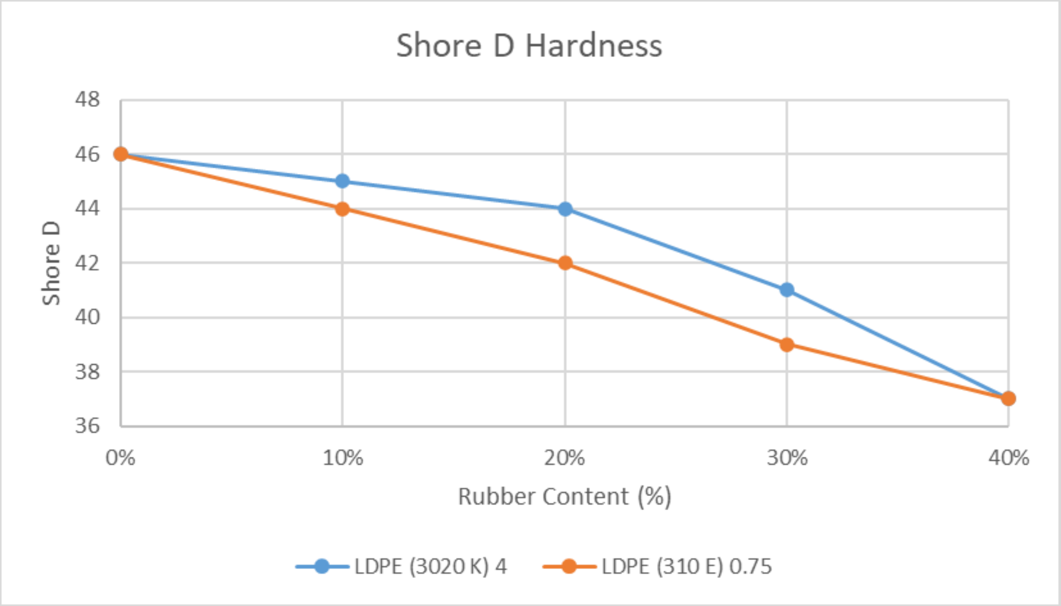
Previous studies on thermoplastic vulcanizates (TPVs) incorporating recycled rubber typically report significantly higher mechanical performance. For example, the work “The Effect of the Recycling Process on the Performance of Thermoplastic Vulcanizates Containing Recycled Rubber from End-of-Life Tires” reports tensile strengths of approximately 25 MPa for TPV without recycled rubber, decreasing to 16 MPa and 10 MPa when incorporating 20 % and 40 % recycled rubber, respectively. Similarly, elongation at break values decrease from around 500 % to approximately 250 % and 100 % as the rubber content increases.

In comparison, the LDPE–GTR blends developed in this work exhibit lower tensile strength and elongation values. Tensile strength ranges from 9–10 MPa for neat LDPE matrices to approximately 6 MPa at 40 wt.% GTR, while elongation at break varies from 76–170 % for the neat polymers to approximately 35–100 % at the highest rubber content.

These differences are mainly related to the processing approach and resulting material morphology. In TPV systems, the rubber phase is typically dynamically vulcanized during processing, leading to a fine dispersion of crosslinked elastomer particles within the thermoplastic matrix. This morphology allows efficient stress transfer and provides high elasticity and ductility.

In contrast, the materials developed in this study consist of simple LDPE/GTR blends without dynamic vulcanization or compatibilizers. As a result, the recycled rubber particles behave mainly as dispersed fillers rather than forming an optimized elastomeric phase. This limits the interfacial adhesion between the phases and reduces the overall mechanical performance of the material.

Nevertheless, the developed formulations still maintain tensile strengths around 6 MPa and elongation values up to 100 % even at 40 % recycled rubber content, which demonstrates that significant incorporation of ELT-derived material is possible while preserving acceptable mechanical properties for semi-flexible applications.



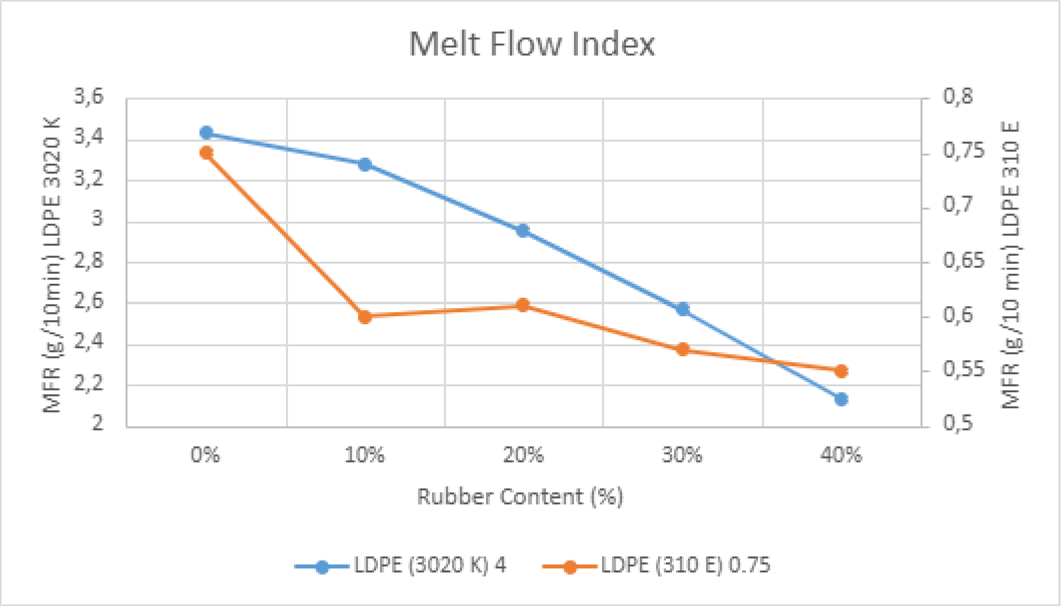
Graph 5 Influence of GTR content on the Shore D hardness of LDPE-based compounds (3020K and 310E).:

The Shore D hardness of the LDPE–GTR compounds shows a gradual decrease with increasing rubber content for both LDPE matrices.

For the LDPE 3020K formulations, hardness decreases from 46 Shore D for the neat polymer to 37 Shore D at 40 wt.% GTR. A similar trend is observed for the LDPE 310E formulations, where hardness decreases from 46 Shore D to 37 Shore D as the rubber fraction increases.

This behaviour is consistent with the incorporation of an elastomeric phase into the thermoplastic matrix. Ground tyre rubber particles are significantly softer than LDPE and therefore reduce the surface hardness of the material as their concentration increases.

The reduction in hardness indicates that the material becomes progressively more flexible and compliant, which is a typical characteristic of thermoplastic elastomer systems. Despite this decrease, the obtained hardness values remain within the range typical for semi-rigid thermoplastic materials, suggesting that the developed compounds may still provide sufficient mechanical resistance for applications such as urban elements, paving components or protective structures.



Graph 6 Influence of GTR content on the MFI of LDPE–GTR compounds.

The melt flow index of the LDPE–GTR compounds decreases as the rubber content increases for both polymer matrices.

For the LDPE 3020K formulations, the MFI decreases from 3.43 g/10 min for the neat polymer to 2.13 g/10 min at 40 wt.% GTR. Similarly, the LDPE 310E formulations show a decrease from 0.75 g/10 min to approximately 0.55 g/10 min over the same rubber content range.

The decrease in melt flow index indicates an increase in the apparent viscosity of the material during processing. This effect is mainly associated with the presence of solid rubber particles dispersed within the polymer matrix, which restrict the mobility of the molten polymer chains and hinder the flow of the material.

Additionally, the rubber particles act as physical obstacles within the melt, increasing the resistance to flow during the MFI test. As the rubber content increases, the flow of the thermoplastic phase becomes progressively more constrained, resulting in lower MFI values.

Despite this reduction, the materials remain processable within conventional thermoplastic processing techniques such as extrusion and injection moulding, which confirms the suitability of these formulations for industrial manufacturing routes.

2.5.3.7 Key observations and recommendations

Processing and manufacturing feasibility

1. Successful compounding up to 40% GTR without processing issues
2. Compatible with standard industrial methods:
    a. Twin-screw extrusion
    b. Injection moulding
3. Stable processing window (190–210 °C)
4. Maintains industrial scalability potential

Implication: Material is ready for mass production of urban elements without needing new manufacturing infrastructure.

Stiffness (Elastic modulus)

Decreases significantly with GTR addition: from~200–222 MPa to ~100 MPa at 40% GTR
Transition from rigid thermoplastic to semi-flexible elastomer-like behavior
Implication for cycling infrastructure:

1. Beneficial for: Lane separators (impact absorption), Bollards (flexibility under collision)
2. Less suitable for: High load-bearing rigid curbs unless reinforced

Tensile Strength

Moderate reduction with increasing GTR: ~9–10 MPa to ~6 MPa at 40% GTR
Caused by: Poor interfacial adhesion (no compatibilizer), rubber acting as stress concentrators
Implication:

1. Still structurally acceptable for: Non-load-critical components, Street furniture
2. Not ideal for: Structural elements under high tensile loads

Ductility / Elongation at Break

Strong dependence on LDPE grade:

1. High-MFI LDPE drops to ~35%
2. Low-MFI LDPE retains up to ~100%

Implication: Excellent for impact resistance & deformation recovery
Critical for: Flexible bollards, Shock-absorbing separators
There is a material selection tip: Use low-MFI LDPE (higher molecular weight) for better durability

Hardness (Shore D)

Decreases from ~46 to ~37 Shore D

Implications:

1. Softer surfaces,
2. Reduce injury risk in collisions
3. Improve safety for cyclists and pedestrians

Therefore, could be recommended for protective barriers and urban safety elements

Processability (MFI)

MFI decreases with rubber content and results in higher viscosity compound. Compound remains still processable with conventional techniques

Implication: no major barrier to manufacturing, but may require slight process optimization at higher GTR (≥30%)

Material Morphology & Limitations

No compatibilizer or dynamic vulcanization used. Rubber acts as inactive filler (not fully integrated phase).

Consequences:

1. Lower mechanical performance vs TPVs
2. Limited stress transfer
3. Interface weaknesses

Improvement potential:

1. Add compatibilizers to promote better bonding
2. Use dynamic vulcanization to grant higher strength & elasticity

Sustainability & Circularity

Up to 40% recycled rubber (ELT) successfully incorporated

Implication: strong alignment with circular economy goals, urban sustainability policies and ideal for eco-friendly cycling infrastructure.

Suitability by application type – recommended applications

Highly suitable for:

1. Flexible bollards
2. Lane separators
3. Shock-absorbing buffers
4. Temporary or modular curbs

Why:

1. Good flexibility
2. Adequate strength
3. Impact resistance
4. Safer deformation behavior

2.5.3.8 Impact on cost and GWP

Impact on cost

Actual prices of available LDPE are around 1,3 EUR/kg

Actual prices of available GTR powders (0,8mm) are around 0,16 EUR/kg

Therefore, the cost reduction **ratio is 1:8** whenever GTR powders (ELT derived powders) substitute virgin LDPE.

Impact on GWP

Value of GWP total for ELT derived powders is negative (-0,773) kg CO_2-eq/kg.

In the worst scenario value of GWP fossil for ELT derived powders is 0,131 kg CO_2-eq/kg.

Values of GWP fossil for LDPE are above 1.8 kg CO_2-eq/kg

Therefore, the GWP fossil reduction ratio is in the **range of 1:13** whenever ELT derived powders substitute LDPE in thermoplastic compounds.

This project has received funding from the European Union's Horizon Programme (HORIZON-CL6-2023-CIRCBIO-02) under grant agreement No 101135406

2.5.4 Example of vulcanised rubber with textile fibre filler

As a novelty in the tire recycling industry, research was undertaken to investigate the possibility of filling rubber mixtures using textiles recovered in the tire recycling process.

Textiles from recycled tires have an extremely low bulk density of approximately 90 kg per cubic meter, which makes it difficult to add them to rubber mixtures. For this reason, before starting the tests, textiles from recycled tires were subjected to a densification process using the pelletization method, obtaining pellets with a bulk density of approximately 400 kg per cubic meter, which can be easily added to rubber mixtures using traditional devices. The textile material prepared in this way was given the name Elitex, which we use in the further discussion of the research carried out.

2.5.4.1 Technical characteristics of pelletized form of ELT-derived textile

Below, the table summarizes the technical characteristics of pelletized form of ELT-derived textile.

Characteristics	Values	Units
Appearance and shape	Cylindrical granules in dark gray (black-gray) color	
Bulk density	410-460	kg/m3
Granule length	5-25	mm
Granule diameter	5-7	mm
Water solubility	Insoluble	-
Humidity	≤ 7, typically 0.5% to 1%	%
Content of small rubber particles below 5 mm	≤ 3	%
Granule strength	5-10	kgf
Granule strength change index	≤ 1.5	-
Synthetic fiber efficiency index	≥ 1.2	-
Processing temperature	<220	Celsius
Length of individual fibers	<5	mm

2.5.4.2 Design of Experiment (DoE) and the objective of the experiment

The study aimed to evaluate how ELT-derived textile fibres affect:

1. processing behaviour (processability)
2. curing characteristics
3. mechanical properties of SBR rubber compounds

with a view to assessing their suitability as a **partial or full replacement for carbon black**.

The DoE systematically varies textile content (0–50 phr) across two formulation strategies (replacement vs addition) and two processing methods, while measuring processing, curing, and mechanical responses to evaluate its feasibility as a filler in SBR rubber.

Two series were investigated:

1. Series A – Constant total filler (50 phr)
    a. Total filler (CB + EX) = constant at 50 phr
    b. Textile replaces carbon black progressively
2. Series B – Variable total filler (50–100 phr)
    a. Carbon black fixed at 50 phr
    b. Textile added additionally on top of 50phr up to 100phr

The purpose was to assess filler loading effect (reinforcement vs dilution).

Table 10 Filling ratio in Series A

Textile [EX] (phr)	Carbon black [CB] (phr)	Total filler (phr)
0	50	50
2.5	47.5	50
5	45	50
10	40	50
15	35	50
25	25	50
50	0	50

Table 11 Filling ratio in Series B

Textile [EX] (phr)	Carbon black [CB] (phr)	Total filler (phr)
0	50	50
2.5	50	52.5
5	50	55
10	50	60
15	50	65
25	50	75
50	50	100

<u>Controlled variables:</u>

1. Rubber matrix: SBR (KER 1502)
2. Cure system: sulfur/CBS/ZnO/stearic acid
3. Antioxidants: TMQ, 6PPD
4. Mixing and curing conditions kept constant

<u>Response variables (measured outputs):</u>

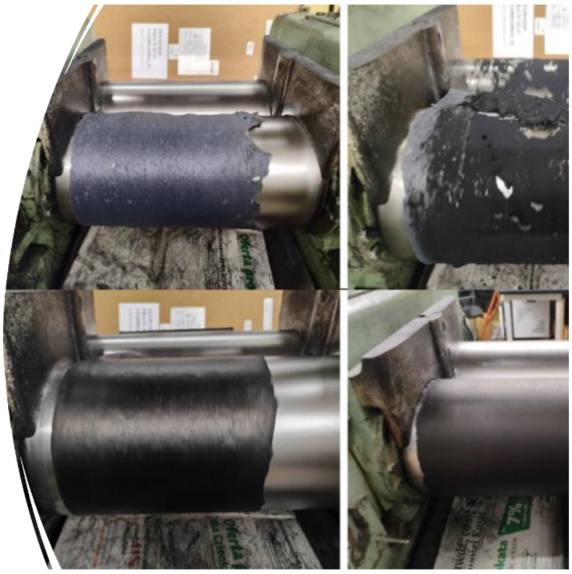
1. Processing & curing behaviour
    a. Mooney viscosity (processability)
    b. Rheometry: ML, MH, ΔM, t10, t90, CRI (cure rate index)
2. Mechanical properties measured after vulcanization:
    a. Tensile strength
    b. Elongation at break
    c. Modulus at 100% and 300%
    d. Hardness (Shore A)

All according to ISO standards, multiple replicates.

2.5.4.3 Results of the experiment

Textile filler processed uniformly and created a homogenous compound as illustrated on the picture to the right and below.

It was noted that the compound filled with textile material presented high resistance to cut through when using the knife, which may suggest interesting feature of the cured compound related with increased anti-vandalism or impact properties of cycling infrastructure rubber products.



Fot. 2 Illustration of uncured samples with various filler loading ratio. Good processability even at textile loading of 50phr (EX50)

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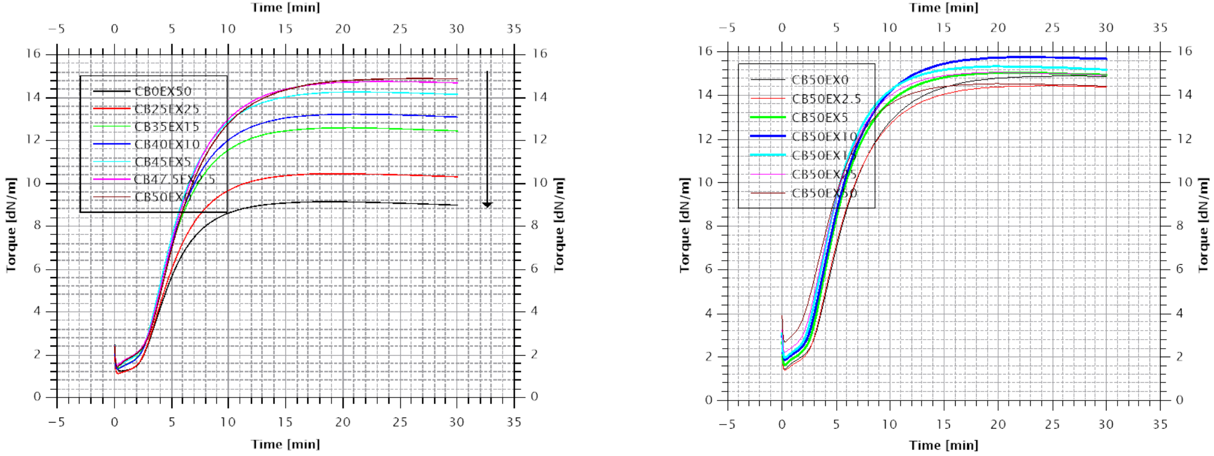
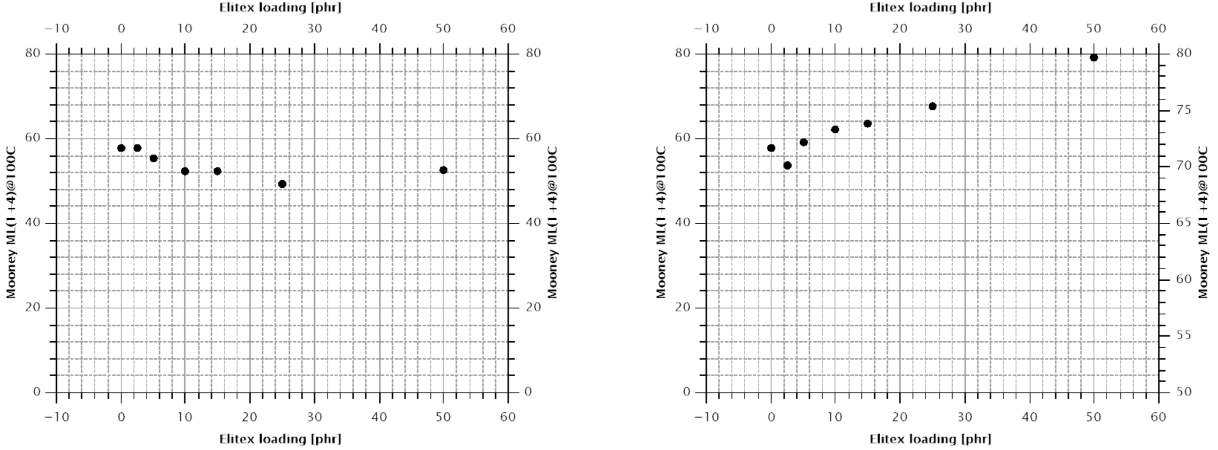
Fot. 3 Illustration of cured samples with various filler loading ratio. Good surface appearance at all textile loading ratios

Curing characteristic:



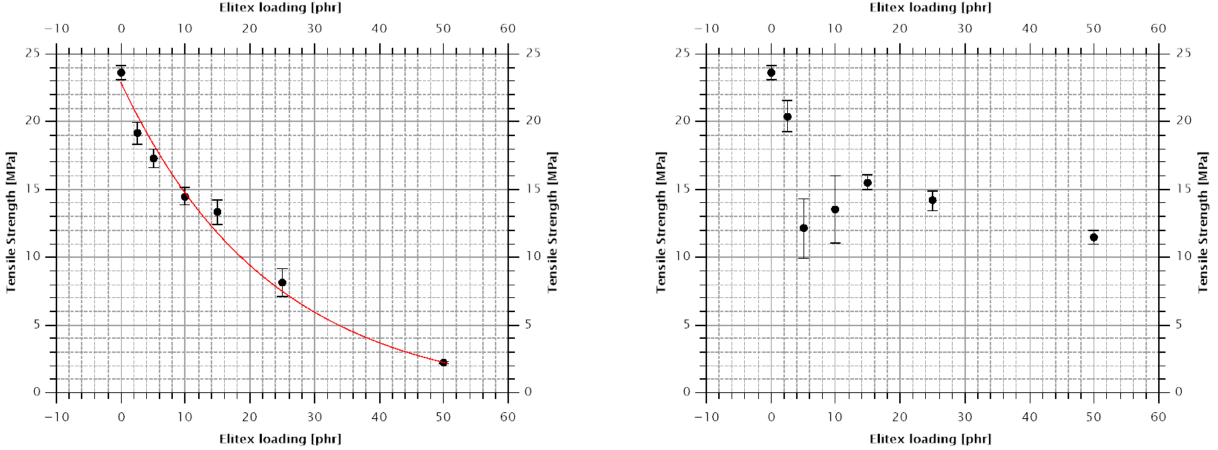
Graph 7 Curing. To the left – Series A – Constant total filler (50 phr). To the right – Series B – Variable total filler (50–100 phr).

Mooney viscosity:



Graph 8 Mooney viscosity. To the left – Series A – Constant total filler (50 phr). To the right – Series B – Variable total filler (50–100 phr).

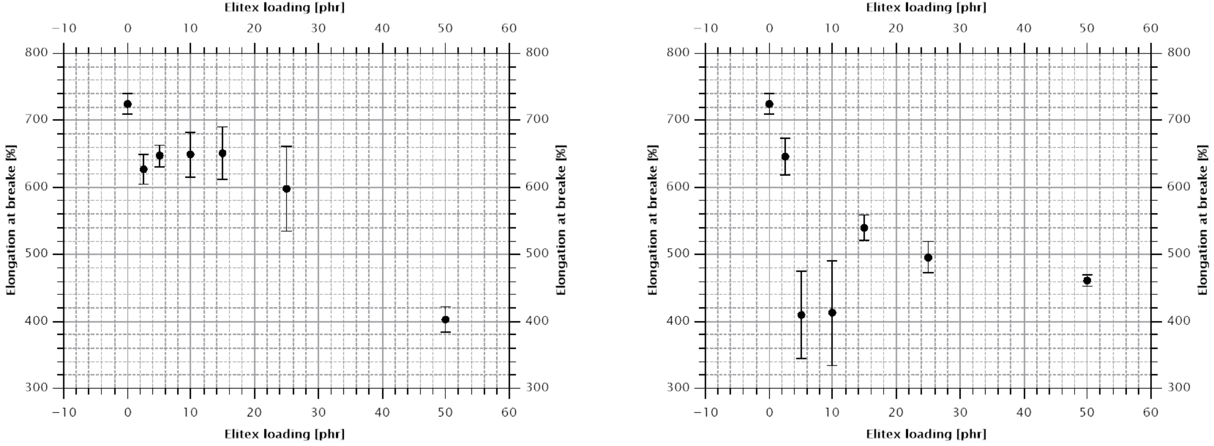
Tensile strength:



Graph 9 Tensile strength. To the left – Series A – Constant total filler (50 phr). To the right – Series B – Variable total filler (50–100 phr).

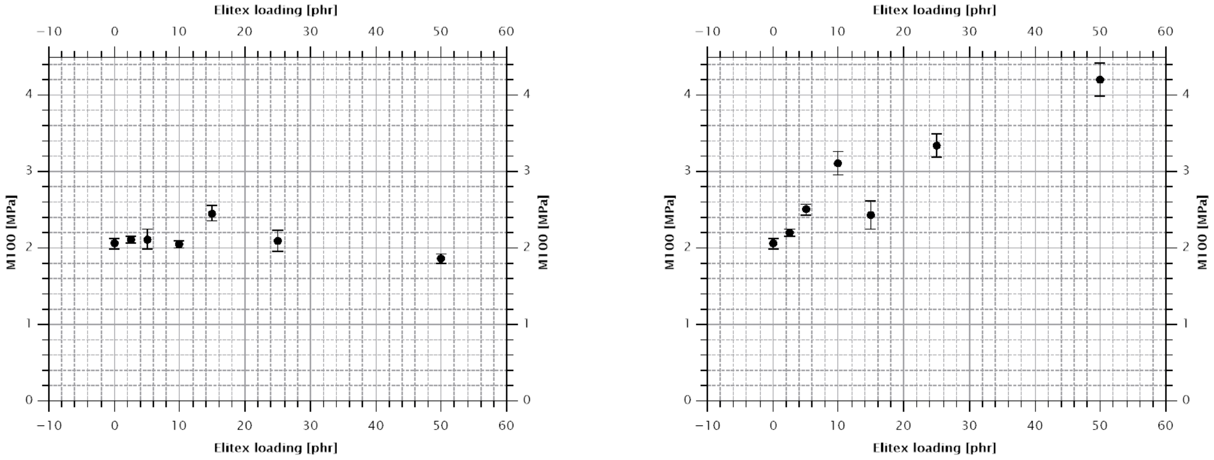
This project has received funding from the European Union's Horizon Programme (HORIZON-CL6-2023-CIRCBIO-02) under grant agreement No 101135406

Elongation at break:



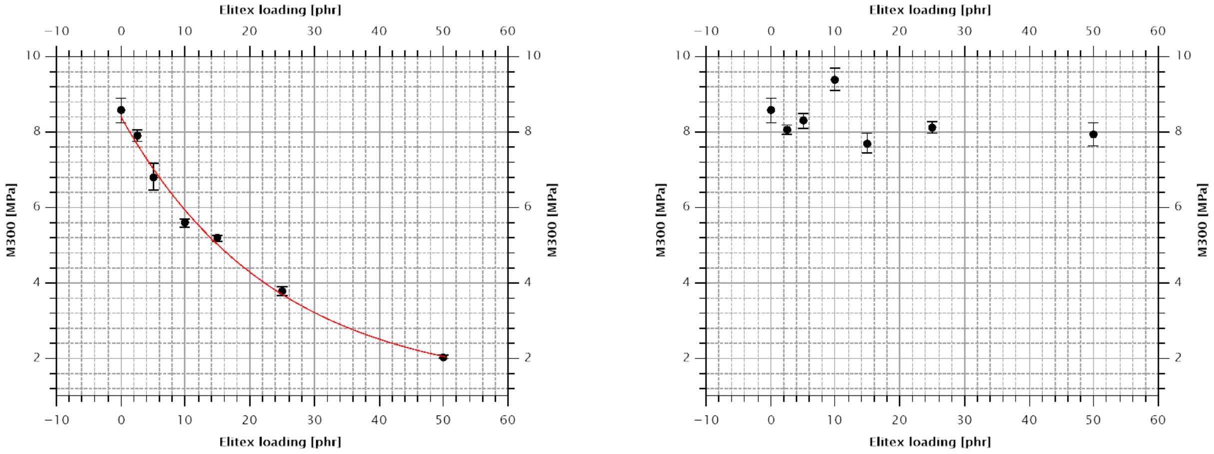
Graph 10 Elongation at break. To the left – Series A – Constant total filler (50 phr). To the right – Series B – Variable total filler (50–100 phr).

Modulus at 100%:



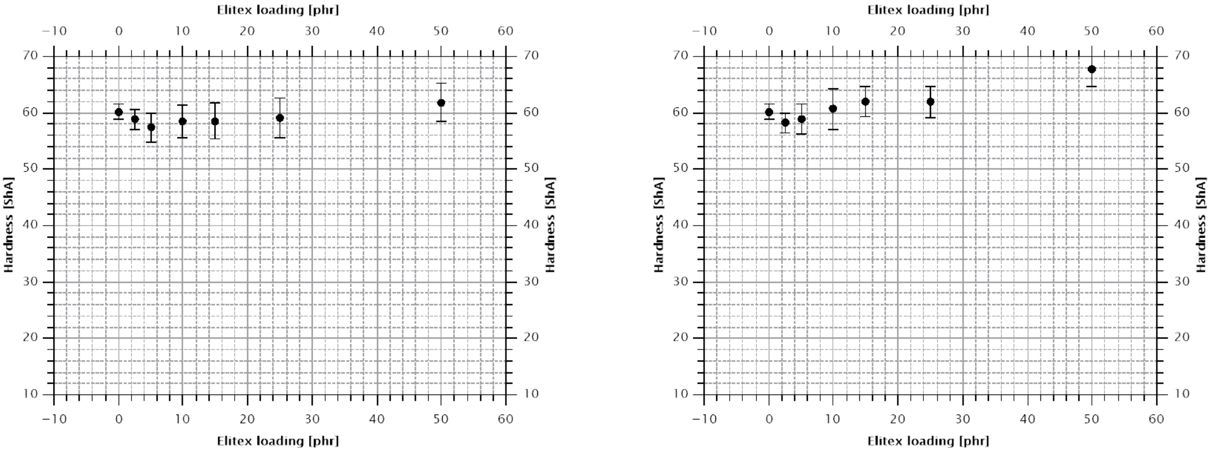
Graph 11 Modulus at 100%. To the left – Series A – Constant total filler (50 phr). To the right – Series B – Variable total filler (50–100 phr).

Modulus at 300%:



Graph 12 Modulus at 300%. To the left – Series A – Constant total filler (50 phr). To the right – Series B – Variable total filler (50–100 phr).

Hardnes ShA:



Graph 13 Hardnes ShA. To the left – Series A – Constant total filler (50 phr). To the right – Series B – Variable total filler (50–100 phr).

2.5.4.4 Key observations

1. Textile filler could be added in the broad loading ratio up to 50 phr without compromising applicability of the compound in manufacturing of cycling infrastructure.
2. Textile filler could be treated as partial replacement of carbon black, contributing to lower production cost and resource utilisation and environmental impact.
3. Textile filler increases hardness of rubber compounds which is a required feature f.ex. for production of snow ploughs, curbs or bolt-down lane separators, speed cushions or impact bases for bollards.
4. The optimal textile fibres alignment (percolation threshold) is observed in the region of 10-15 phr loading ratio
5. Textile filler increases the resistance to cut through the rubber product.
6. Textile filler increases the Mooney viscosity of the uncured compound enhancing the processability.
7. Textile filler processes equally good in closed and open mixers.

2.5.4.5 Impact on cost and GWP

Impact on cost

Actual prices of available textile fillers are around 0,35 EUR/kg
Actual prices of available SBR rubber are around 1,75 EUR/kg
Actual prices of available carbon black are around 1,2 EUR/kg
Therefore, the cost reduction **ratio is 1:5** (SBR) and **1:3,4** (CB) whenever textiles substitute synthetic rubber or virgin Carbon Black.

Impact on GWP

Value of GWP total for ELT derived textiles (Elitex) is negative (-0,0137) kg CO_2-eq/kg.
In the worst scenario value of GWP fossil for ELT derived textiles (Elitex) is 0,214 kg CO_2-eq/kg.
Values of GWP fossil for synthetic SBR rubber are above 2.6 kg CO_2-eq/kg
Values of GWP fossil for virgin Carbon Black are above 2.4 kg CO_2-eq/kg
Therefore, the GWP fossil reduction ratio is in the **range of 1:11** whenever textiles substitute synthetic rubber or virgin Carbon Black.

3 CONCLUSION

3.1 Main findings and outputs

All investigated compounds, formulated through combinations of elastomers, polypropylene (PP), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and ELT-derived powders and textile fibres, have been demonstrated to be technically viable and highly promising for applications in cycling lane infrastructure. This is particularly evident in use cases requiring impact resistance, flexibility, cost efficiency, and enhanced sustainability.

The studied materials function effectively as sustainable fillers, offering a significantly reduced carbon footprint and notable cost advantages compared to conventional materials. In addition, certain formulations exhibit enhanced or unique functional properties not typically observed in virgin materials used for cycling infrastructure applications. The table below summarizes the key findings of the study.

Base materials	**ELT derived components**		
	Fibres	Powders	Devulcanised rubber
Thermoplastics	Eco-filler Cost saver **Performance enabler**	**Charpy impact** Eco-filler Cost saver	**Charpy impact** Eco-filler Cost saver
Rubber compounds	Eco-filler Cost saver **Cut-through protection** **Mooney regulation** **Hardness regulator**	**Processing add** Eco-filler Cost saver	Eco-filler **Cost saver**

Technical feasibility confirmed

1. ELT-derived materials (**crumb rubber, powders, textile fibres**) can be successfully incorporated into:
    - thermoplastics (HDPE, PP, LDPE)
    - elastomeric systems (vulcanized rubber, devulcanized rubber)
2. Multiple processing routes are viable:
    - reactive sintering
    - devulcanization/reclaiming
    - rubber compounding
    - melt blending

Wide applicability across product types

ELT-derived materials are suitable for manufacturing key cycling infrastructure elements:

- bollards (including elastic/vulcanized types)
- lane separators and modular kerbs
- speed bumps and traffic calming elements
- rubber curbs and tiles
- drainage systems
- sign bases and protective elements

Mechanical performance is sufficient for application

1. Required mechanical thresholds for urban furniture are relatively low (≈2 MPa tensile strength), enabling:
    - high substitution rates of virgin materials
2. Reactive sintering already meets minimum requirements for many products

3. Advanced methods (compounding, devulcanization) provide **significantly improved performance**

Melt-blended thermoplastics show high industrial potential

1. Tensile strength retention: **65–87% vs virgin polymers**
2. Impact resistance:
   - increases with recycled content
   - can exceed virgin polymer performance (up to **~172%**)
3. Particularly suitable for:
   - impact-prone elements (bollards, separators)

Rubber compounding enables high-performance materials

1. Highest mechanical performance among tested methods
2. Enables:
   - high recycled content (>70%)
   - controlled property tuning
3. Textile fibres identified as:
   - **high-performance filler**
   - superior to conventional fillers (e.g. $CaCO_3$, talc)
   - retention values: **40–90%**

Devulcanization improves material quality

1. Produces materials with:
   - significantly higher tensile strength vs reactive sintering
2. Key factors:
   - finer particle size guarantee better performance
   - feedstock type (truck tyre treads best, than passenger tyres and mixed feedstock)

Environmental and economic advantages

1. ELT-derived materials show:
   - **negative or very low GWP values**
   - significantly lower CO_2 footprint than virgin materials
   - GWP fossil reduction ratio in the **range of 1:11** whenever textiles substitute synthetic rubber or virgin Carbon Black
2. Cost advantage:
   - GTR powder ~€0.16/kg vs HDPE/PP ~€1/kg
   - substitution ratio ~**1:6 cost reduction**

Processing feasibility validated

1. Industrial processes confirmed:
   - extrusion (twin-screw)
   - injection moulding
2. No major processing issues observed for:
   - up to **30–40% rubber loading in thermoplastics**

3.2 Results achieved to be used in the project

Project will focus on application of ELT-derived materials for manufacturing of key cycling infrastructure elements:

- bollards (including elastic/vulcanized types)
- lane separators and modular kerbs
- speed bumps and traffic calming elements
- rubber curbs
- drainage systems

  - sign bases and protective elements

Project will explore textile fibres identified as high-performance filler, superior to conventional fillers (e.g. $CaCO_3$, talc), with retention values: 40–90%.

Project will explore melt-blended thermoplastics that show high impact resistance increases with recycled content, that can exceed virgin polymer performance (up to ~172%), particularly suitable for impact-prone elements (bollards, separators).

3.3 Results achieved to be used for future exploitation

For future exploitation, it is strongly recommended to investigate in greater depth the influence of tyre sorting and deconstruction on the mechanical performance of reclaimed and devulcanized rubber materials. The homogeneity and chemical consistency of the feedstock are critical factors governing the quality and reproducibility of the final products.

In this context, the development and industrial implementation of advanced tyre deconstruction technologies should be considered a priority. As such technologies are currently not widely established in global recycling practice, their advancement presents a significant opportunity to create a **competitive advantage for the European recycling and materials industry**. By enabling the recovery of chemically defined rubber fractions, Europe could position itself as a leader in high-quality, application-specific recycled materials, strengthening both technological sovereignty and circular economy performance.

Furthermore, additional research is recommended to explore higher loading ratios of ELT-derived rubber powders in thermoplastic matrices, with the objective of maximizing recycled content while maintaining acceptable mechanical and processing properties.

Finally, the effects of compatibilizers, coupling agents, and curing systems across all compounding and blending methods should be systematically investigated, as these additives have the potential to significantly enhance interfacial adhesion, mechanical performance, and overall material stability.

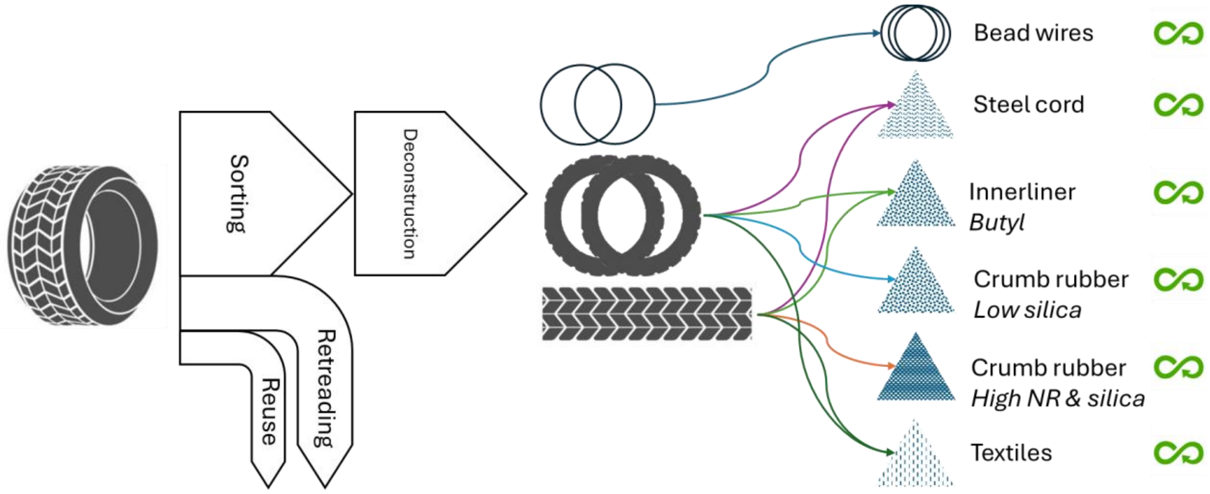


Figure 1 Competitive advantage for the European recycling and materials industry through sorting and deconstruction of tyres

3.4 Results achieved to be disseminated

All performance related data should be disseminated with the special attention to increase of impact resistance, applicability of textile materials, cost advantages and GWP reduction.

To achieve sustainable results SMILE CITY project should disseminate information on postulated improvements in recycling methods and infrastructure:

Need for advanced tyre sorting systems

1. Current situation:
    - sorting rarely performed, mostly manual

2. Recommended improvements:
    - automated sorting systems
    - classification by: tyre type (PC, TT, OTR) / composition (tread vs whole tyre)

Impact: directly improves final mechanical performance of products

Importance of tyre deconstruction

1. Strong recommendation to implement:
    - separation into tread, carcass, inner liner
2. Benefits:
    - recovery of chemically homogeneous materials
    - improved compatibility in recycling processes

Optimization of feeding strategies

1. Current limitations:
    - fixed or random feeding reduces consistency
2. Recommended:
    - **adjustable dosing systems** for PC/TT ratio

Impact: enables tailoring of: mechanical properties, process stability, product performance

Shift toward performance-controlled recycling

1. Transition from:
    - bulk recycling → **engineered material production**
2. Key parameters to control:
    - particle size
    - feedstock composition
    - process conditions

Integration with circular economy frameworks

1. ELT materials contribute to:
    - EUDR compliance (deforestation-free materials)
    - CSRD / net-zero targets
2. Strong recommendation:
    - integrate ELT recycling into **urban infrastructure supply chains**