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Recovery methods, material characterization, and performance assessment of recycled thermoplastic road markings

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ABSTRACT

Thermoplastic road markings are essential for traffic safety but contribute significantly to environmental impacts due to the energy-intensive production of key components such as pigments, binders, and glass beads. This study presents a novel investigation of the feasibility of recycling thermoplastic road marking materials by comparing two removal techniques: high-pressure water blasting (WB) and mechanical milling (MM). WB produced fine-grained materials contaminated with bitumen and silt, limiting their recyclability without further processing. In contrast, MM yielded coarser thermoplastic fractions that were more amenable to reuse, although the process also introduced substantial asphalt contamination due to the unintentional removal of surrounding pavement. Overall, the findings demonstrate that recycling thermoplastic road markings is technically viable, with MM offering superior material quality and performance despite contamination challenges, while WB provides a less invasive removal method but lower recovery efficiency. Recycled materials were first thoroughly analyzed for particle size distribution, glass bead quality, binder, TiO_2, and premix content in lab, and thereafter incorporated into new thermoplastic formulations at 10 %, 20 %, and 30 % replacement levels by weight. The modified materials were applied and assessed in real traffic at the NordicCert road trials. Initial testing of road markings with recycled materials revealed that the brightness decreased with higher recycled content. However, MM with up to 20 % recycled content met all performance requirements for white road markings at the initial tests at the road trials, including $R_L \geq 150$ mcd/m^2/lx, $Q_d \geq$ 130≥ mcd/m^2/lx, chromaticity coordinates, and skid resistance (≥ 50 SRT units) and long-term performance assessments are ongoing. This research provides foundational knowledge for integrating circular economy principles into sustainable road marking practices.

1. Introduction

Road markings play a vital role in traffic control, safety, and organization on roadways by providing visual signals that guide and manage the flow of traffic [35]. They work in tandem with other road equipment such as traffic signs and signals, to communicate regulatory, warning or guidance messages to drivers, cyclists, and pedestrians, which helps prevent accidents and ensures orderly movement on the roads [16]. To effectively serve their purpose, road markings must meet high standards of functionality under various conditions, including visibility in wet weather and at nighttime. In addition to visibility, road markings must also meet strict

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requirements for skid resistance, color, and durability, to ensure long-term effectiveness and safety [10,11,8]. Road markings are categorized into longitudinal (along the road, e.g., lane and edge lines), transverse (across the road, e.g., stop lines and pedestrian crossings), and others (e.g., arrows, text, and symbols), with different requirements on their functional parameters (e.g., coefficient of retroreflected luminance R_L, luminance coefficient under diffuse illumination Q_d, luminance factor β, (x,y) chromaticity coordinates, and skid resistance).

Most longitudinal lines face regular traffic, but some, particularly in urban areas, are exposed to heavy loads [22], while the left edge line typically sees low traffic. To reduce wear, many countries use recessed edge and center lines where material is applied in milled grooves flush with or slightly below the asphalt surface, unlike traditional markings that protrude 1.5–5 mm. Though more expensive initially, this method has proven effective in lowering maintenance needs, especially in areas with frequent winter road maintenance [20,21].

Transverse markings are frequently found in urban areas with large traffic loads and complex traffic situations [2,24,38]. Transverse road markings often experience substantial wear and commonly require annual maintenance, especially in regions with frequent winter road maintenance or studded tire usage. As vehicles drive over road markings, they gradually wear down, generating microplastics and fine particles [25,37,42,43]. These microplastics can be released into the environment, causing air pollution and potentially affecting marine and terrestrial ecosystems when washed into waterways [26].

Table 1
Binder type and binder content, polymer content, other constituents and typical applied thicknesses for common road markings systems [1,15,23,39,4]. Definitions of material types are taken from EN 1871 [11] and EN 1791 [8]. N.B. Solvent-based paint has been excluded because its use is prohibited in many countries, among others, the Nordic ones.

Type	Binder	Polymers	Other raw materials
Thermoplastic, 1.5–4 mm "*Solvent-free marking products which are supplied in a block, granular, powder forms or performed (e.g. as tape), which is heated to a molten state prior to application to road surfaces, and which forms a cohesive film by cooling.*" (EN1871)	15—22 % Modified rosin esters, C5 hydrocarbon resin, C9 hydrocarbon resins and their mixtures.	1—5 % Usually, additives in the form of plasticizers such as SIS (styrene-isoprene-styrene), SBCs (styrene-block-copolymers), or EVA (ethylene-vinyl acetate).	▪ Glass beads ▪ Calcium carbonate, sand, or other inorganic fillers ▪ Titanium dioxide or organic pigments ▪ Additives such as oils and waxes Additional glass beads and anti-skid aggregates are sprinkled over the surface at application.
Water-based paint, 0.4–0.6 mm "*Liquid products which contain binders, pigments, fillers, solvents, and additives, which can be supplied in single or multi-component systems and which, when applied, produces a cohesive film by the process of water evaporation or the process of water evaporation and a chemical reaction or coalescence process.*" (EN 1871)	15—25 % Methyl methacrylate (MMA) or other acrylates.	15—25 % The binder is a polymer or forms a polymer during curing.	▪ Calcium carbonate, talc, nepheline syenite, or other inorganic fillers ▪ Titanium dioxide or organic pigments ▪ Additives such as plasticizers, defoamers, coalescent agents, dispersants, other chemicals ▪ Water, organic co-solvents (like ethanol and/or ammonia) Glass beads and anti-skid aggregates are sprinkled over the surface at application.
Cold plastic, 1.5–4 mm "*Viscous products supplied in multi-component forms (at least one main component and a hardener system), the cohesive film being formed after mixing of all components only by a chemical reaction following which the cold plastic becomes a solid.*" (EN 1871)	25—35 % Usually methyl methacrylate (MMA), other acrylates, or epoxy, urethane or urea.	25—35 % A polymer is formed during curing.	▪ Glass beads ▪ Calcium carbonate, sand, or other inorganic fillers ▪ Titanium dioxide or organic pigments ▪ Additives such as plasticizers, initiators, stabilizers, accelerators, retarders, or other chemicals Additional glass beads and anti-skid aggregates are sprinkled over the surface at application.
Tape, 3 mm "*Preformed multilayer road marking, capable of adapting itself to the texture of the substrate, which may be precoated with pressure-sensitive adhesive, capable of being stuck to the substrate without heating the material, while the photometric, colorimetric and skid resistance characteristics are not significantly modified during application.*" (EN 1790)	60—90 % Polyurethane.	60—90 % The base material is a polymer.	▪ Calcium carbonate, sand, ground ceramic particles ▪ Titanium dioxide or organic pigments ▪ Additives such as organic chemicals, rubber, and plasticizers Glass beads and friction agents are embedded on the surface of the tape.

1.1. Road marking materials

There are various types of road marking materials available globally, and their usage in different regions is influenced by factors such as climate, traffic volume, regulations, and local traditions. The four primary material categories are paint (water- or solvent-based), thermoplastic materials, cold plastic materials (sometimes referred to as reactive, plural or multi-component systems), and road marking tape [11,8]. In Sweden and across the Nordic region, thermoplastic materials are the most widely used due to the challenging climate with varying temperatures, frequent winter road maintenance, and the use of studded tires [22,27], while water-based paint is the most common material on a global scale [31].

Road markings are typically applied as assemblies, consisting of a base material – thermoplastic, paint, or cold plastic – along with a drop on material (glass beads, anti-skid aggregates or a mixture of the two), Table 1. The selection of material and the specific compositions depend partly on climatic conditions, but mainly on the intended use and function. All materials consist of pigments and fillers, held together by a binder, often of polymeric origin. Most materials also contain significant amounts of glass beads to ensure the retroreflective function of the road marking.

1.2. Climate and environmental impact of thermoplastic road marking materials

Thermoplastic road markings have a notable climate and environmental impact, largely due to the raw materials used i.e., pigments, glass beads, and binders, which contribute to substantial emissions. Extending the lifespan of road markings is key to reducing their impact [28] and more durable materials like thermoplastics and cold plastics, when properly applied, have a lower total environmental footprint than alternatives such as water-based paints and tapes due to less frequent maintenance and reduced total material use (Cruz et al., 2016; Burghardt & Pashkevich, 2022).

Around 40 % of thermoplastic road markings consist of premix glass beads. The purpose of the glass beads is to provide retroreflective properties once the drop on glass beads have worn off. While both premix and drop on glass beads are primarily made from recycled float glass (silicate glass), the production of the beads is highly energy-intensive due to the need to operate the glass-melting gas-fired furnaces at temperatures ranging from 1500 to 1700 °C, resulting in significant greenhouse gas emissions and high energy consumption.

Titanium dioxide is the primary pigment in road marking materials, and its production poses several environmental and geopolitical challenges [13]. The manufacturing process is highly energy-intensive, leading to significant greenhouse gas emissions and contributing to climate change [29,30]. Additionally, titanium mining causes severe environmental damage, including biodiversity loss, deforestation, and extensive land degradation. The chemical processes involved also generate large amounts of waste and pollutants, negatively affecting air and water quality. Beyond environmental concerns, titanium dioxide production has geopolitical implications. A significant portion of global titanium supply originates from politically unstable regions, raising risks related to supply chain security, human rights violations, and conflict financing. Estimates are that around 10 % of global titanium production comes from highly unstable countries, where poor labor conditions and worker exploitation are common [18,19].

Advancements in the properties of thermoplastic road markings such as the use of bio-renewable resins and natural modified rosins instead of polymers have been reported [31,45,44]. However, these improvements alone are insufficient. It is equally crucial to address the challenges associated with resource consumption by promoting material reuse as the primary solution for sustainability.

To the best of our knowledge, this is the first study to investigate the recycling of thermoplastic road marking materials. As a proof-of-concept, the aim is to assess the feasibility of recycling through initial testing focusing on removal methods, material properties, and monitoring of performance in real traffic conditions. Water blasting and mechanical milling were evaluated as viable removal techniques. A comprehensive analysis of the recycled material was conducted, evaluating its characteristics and properties to determine its suitability for reuse. The recycled material was then incorporated into new formulations containing 10 %, 20 %, and 30 % recycled content by weight. These formulations were applied and tested under real traffic conditions at the NordicCert road trials in Norway. Initial measurements of key performance parameters visibility, color, and friction have been conducted, with follow-up evaluations planned after one and two years.

2. Method

2.1. Collecting road marking materials for recycling

Mechanical milling (MM) was carried out on a 15 cm-wide longitudinal intermittent lane marking that had been applied 12 months prior and was subsequently removed due to road construction. The road marking consisted of a white thermoplastic extrusion material, certified by NordicCert in roll-over class P5. This same material was used both as the reference and as the base for the recycled formulations. The thickness was approximately 3 mm. Milling was carried out using a cold milling machine fitted with a 50 cm milling drum and diamond-tipped teeth spaced at 3 mm intervals, specially configured for precision milling.

High-pressure water blasting (WB) was conducted at various sites during the spring and summer of 2024. This method utilizes rotating heads equipped with 40 000 psi water jet nozzles to remove road markings. The machine featured two independently operated blasting heads and an integrated de-watering system, allowing the recovered material to be collected in a mostly dry state. Used water was collected, treated on-board the truck, and properly disposed of following cleaning.

2.2. Recycling processes

The two primary methods for collecting road markings: mechanical milling (MM) and water blasting (WB) yield materials with distinct characteristics. Mechanical milling retrieves larger flakes and fragments of thermoplastic road markings, mixed with gravel, pieces of asphalt, and finer particles such as sand and road dust, Fig. 1. In contrast, water blasting primarily produces finer fractions, devoid of coarse fragments, Fig. 2. Alongside road marking particles, the collected WB material also contains sand, silt, clay, and bitumen residues. Given the variability in the properties of the recovered materials, the recycling process must be adapted accordingly to accommodate these differences.

The first step of separation of the thermoplastic material collected with mechanical milling from asphalt, gravel and fine particles, was carried out using a motorized vibrating screen shaker with standard testing screens in sizes 16 mm – 10 mm – 8 mm – 4 mm – 2 mm, with subsequent washing of the material using tap water. Thereafter, the thermoplastic material was separated from the remaining gravel and asphalt by manual sorting. Only fractions larger than 8 mm were sorted, see Fig. 1. After the first coarse sorting, the material was melted and allowed to flow through a 3-mm metal mesh to ensure that large particles, which could potentially damage the application equipment, were no longer present in the material. The thermoplastic material was allowed to solidify in aluminum molds that could be easily added to new material batches.

The recycled material was then mixed with virgin raw materials according to the manufacturer's product specification. The addition of recycled mechanical milling material in the batches was 10 %, 20 %, and 30 % by weight, respectively.

The collection of materials by water blasting (WB) resulted in material batches with varying properties. Generally, the materials consisted of fine fractions, but varying amounts of clayey material caused some batches to clump together, see Fig. 2. In total, eight materials were selected for initial analysis. Of those, the three most promising candidates were selected for preparing new road marking formulations. No additional preparations were carried out prior to mixing with virgin raw marking materials. The addition of recycled WB material in the batches was 10 %.

2.3. Laboratory analyses

Table 2 provides a comprehensive overview of the laboratory analyses for the materials, and the measured performance parameters for the materials applied on the road trials. It should be noted that the raw materials obtained from water blasting consist of eight different batches (labeled WB1-WB8). Each of these eight materials was evaluated with respect to color (including the luminance factor β and (x,y) chromaticity coordinates). Based on this, the three most promising materials (WB4, WB6, and WB8) were selected for addition to new thermoplastic road marking formulations and continued analysis, including binder, premix, and TiO_2 content, and determination of color, softening point, and indentation value. Out of a total of six formulations with recycled thermoplastic material, three were selected for application and testing at the NordicCert road trials in Norway.

For determination of particle size distribution, an orbital sieve shaker with standard test sieves ranging from 0.063 mm to 16 mm were used. The total sieving time was 5 min. The proportion of thermoplastic road marking was only determined for the material collected by mechanical milling, and was limited to particle sizes > 2 mm. The percentage thermoplastic road marking was determined by mass, using an analytical balance, with an accuracy of 0,1 g and zero-point correction.

The binder content and the premix content were determined in accordance with the methods described in EN 12802 [6]. TiO_2 content was calculated from the determination of titanium content by ICP-SFMS according to EN ISO 17294–2 [9] after $LiBO_2$ fusion.

The softening point was determined according to the Wilhelmi method, following the procedure described in EN 1871 [11], using glycerol as test liquid. Also, determination of the indentation value of the thermoplastic road marking materials followed the description in EN 1871.

The color includes the luminance factor β and the (x,y) chromaticity coordinates of the materials. The measurements were carried out according to EN 1436 [10] and EN 1871 [11], using a portable spectrophotometer with measurement geometry 45°/0°, 2°

Fig. 1. From left to right: (1) Recovered MM as collected, containing a mixture of thermoplastic road marking, asphalt residue, gravel, and dust; (2) material after the initial sieving step; (3) material during the washing process; and (4) cleaned and processed material following sieving, manual sorting, and washing.

Fig. 2. Eight material samples collected using high-pressure water blasting.

Table 2
Overview of laboratory analysis and field testing of road marking systems with recycled thermoplastic material.

	Mechanical milling (MM)				**Water blasting (WB)**	
Laboratory testing	raw material	10 %	20 %	30 %	raw material	10 %
Particle size distribution	x				x	
Proportion of thermoplastic material	x					
Binder content	x	x	x	x	x	x
TiO_2 content	x	x	x	x	x	x
Premix content	x	x	x	x	x	x
Softening point		x	x	x		x
Indentation value		x	x	x		x
Color		x	x	x	x	x
Light microscopy	x				x	
Applied on test side for road trials		x	x	x		
Coefficient of retroreflected luminance and luminance coefficient under diffuse illumination		x	x	x		
Color (luminance factor and chromaticity coordinates)		x	x	x		
Skid resistance		x	x	x		

standard observer and standard light D65. Average values were calculated from 10 individual measurement points for both fine grained materials (1—2 mm) collected by water blasting, for pieces of material (1—2 cm) collected by mechanical milling, and for laboratory samples prepared by melting and mixing with recycled thermoplastic materials collected by both water blasting and mechanical milling.

A stereo microscope equipped with a digital camera, was used to evaluate the quality of glass beads in the collected materials. The quality assessment was based on the type of defects listed in EN 1423 [7].

2.4. Road trials

All road marking materials used for state roads in Denmark, Finland, Iceland, Norway, and Sweden must be tested and certified in Nordic climate and conditions. Currently, this is carried out by *Nordic certification of road marking materials system, NordicCert*. The certification assesses performance in road trials, fulfilling the requirements in EN 1824 [12], evaluating the performance parameters coefficient of retroreflected luminance (R_L) under dry and wet conditions, luminance coefficient under diffuse illumination (Q_d), skid resistance (SRT), and (x,y) chromaticity coordinates. Performance measurements are conducted one and two years after application, and materials are classified based on their durability with respect to the roll-over classes they withstand with fulfilled performance.

The location for the road trials used for evaluation of the recycled thermoplastic materials is in eastern Norway, along Rv 2, about 180 km northeast of Oslo. It is situated on a straight, flat 9 m two-lane rural road with posted speed limit of 90 km/h speed limit. The surface is a stone matrix asphalt (SMA 11) applied in 2022, with a roughness class RG2 (mean texture depth 0.60–0.90 mm). The annual average daily traffic (AADT) is approximately 3200 vehicles per day, with heavy vehicles accounting for about 15 % of the total traffic [36]. It is estimated that 50–55 % of the vehicles use studded tires in the winter period. Additional information about the test site can be found in *Nordic certification system for road marking materials version 10–2024* [17].

At the road trials, annual measurements are conducted for both traffic volume and the transversal distribution of wheel passages. Materials for testing are applied as rows of ten lines in the direction of the traffic, see Fig. 3. Each line is 250 cm in length and 15 cm in width. The thicknesses of the road markings are 1.5 mm for thermoplastic spray materials and 3 mm for thermoplastic extrusion materials.

2.5. Application of materials on the road trials

In September 2024, three thermoplastic road marking materials containing 10 %, 20 %, and 30 % recycled MM thermoplastic, respectively, were applied at the NordicCert road trials. The tested materials were applied as 3 mm thick, flat (type I) markings using a manual screed box (15 cm wide) to ensure uniform thickness and adhesion. The application process involved heating the thermoplastic materials to temperatures between 180–220 °C until they liquefied. For this, powder mixtures of virgin thermoplastic material were introduced to a pre-heater melting kettle and once the powder material was melted, blocks of recycled thermoplastic material were added to the mixture. The melting kettle was equipped with an indirect oil-heating system and hydraulic stirring to mix the materials efficiently. Once the application temperature was reached, the material was allowed to fully homogenize at this temperature for one hour prior to application.

The materials were applied in dry conditions with wind speeds of 3—4 m/s, road surface temperatures of 13—17 °C, air temperatures of 13—15 °C, and a relative humidity of 62—68 %.

Each material was applied in ten longitudinal lines (250 cm in length, 15 cm in width, and 15 cm apart), nine within the traffic lane and one on the shoulder as a reference with no wheel passages. The application proceeded without any deviations, and the recycled materials behaved in the same way as formulations with 100 % virgin raw materials.

The thickness of the lines was controlled at application. For each row of lines, a pre-weighed steel plate (see Fig. 7) was placed in the end of one of the lines where the highest number of wheel passages was expected. The thickness of the material was measured on the steel plate without any drop on glass beads or aggregates and the mean thickness was calculated from the weight and the known density of the materials. In addition, the thicknesses of a random sample of lines were controlled by a portable measurement tool. All materials met specification, with thicknesses of 2.9 mm, 3.1 mm, and 3.1 mm (within the 3.5 mm limit).

In connection to the thermoplastic material application, drop on-materials (glass beads mixed with anti-skid material), comprising 80 % glass beads (180–850 µm) and 20 % glass granulates (250–850 µm), were applied at 350–430 g/m^2 using a custom-built spreader.

Proper embedment of drop-on materials (50–60 % of bead diameter) was achieved, critical for optimal retroreflectivity (R_L). This depends on the thermoplastic viscosity, which is temperature sensitive. Excessive temperature can cause beads to sink too deeply, while low viscosity can hinder proper embedment. No significant differences in viscosity or embedment behavior were observed between recycled and virgin material formulations.

Samples were collected during application for laboratory analysis, and performance monitoring at the road trials will continue over a two-year period, with the first evaluation scheduled for September 2025.

3. Results and discussion

3.1. Recycling process

High-pressure water blasting leaves fewer scars on the road surface than removal by mechanical milling, making it the assumed preferred method, however, it still removes the surface layer of bitumen and polishes the surface of the stone aggregates. The degree of stripping depends on the water pressure and the forward speed of the removal truck. Truck-mounted mobile high-pressure water blasting systems have a water and debris vacuum suction system that leaves the surface cleaner than milling operations. The trucks also

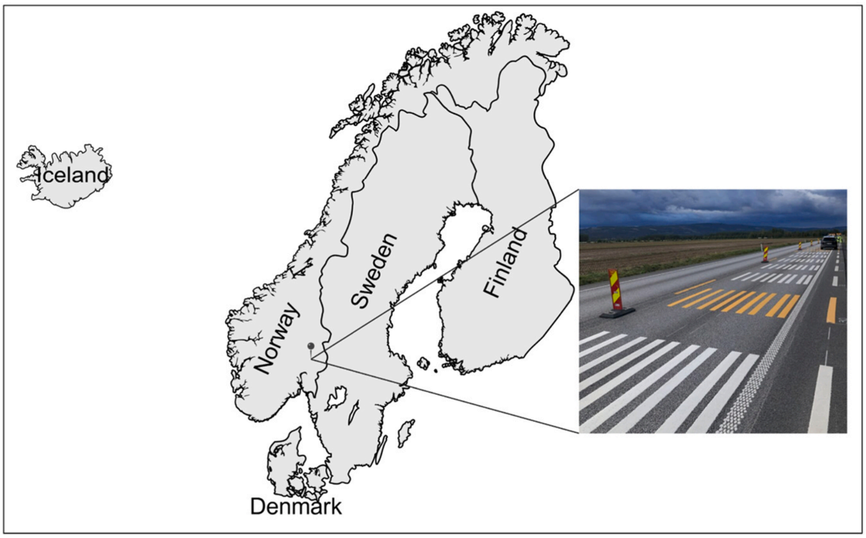

Fig. 3. Location of the road trials and examples of materials applied for testing.

have efficient water purification systems, making it possible to discharge the water without further action [3]. Nevertheless, the benefits of the gentle removal process are hampered by the limitations in efficiency when it comes to separation of recovered road marking material from residual material such as fine particles of bitumen, clay, silt and sand.

For mechanical milling, other issues arose. In this study, the milling drum used for mechanical milling had a width of 50 cm, whereas the road marking measured only 15 cm. Consequently, approximately 35 cm of asphalt was removed unnecessarily, which hindered the recycling process by introducing an excessive amount of gravel and asphalt residues into the recovered material. To improve the efficiency of both the removal and recycling processes, future studies are advised to perfect the milling for the specific application and adapt the process with regards to milling width, milling depth and vehicle speed to avoid unnecessary asphalt removal.

To assess whether mechanical milling or water blasting processes cause damage to the glass beads, subsamples of MM, WB4, WB6, and WB8, where the binder and pigment had been removed, were examined under a stereo microscope, Fig. 4. The size fractions were between 0.063 mm and 1 mm. Only a few glass beads exhibited visible damage, less than the up to 20 % maximum weighted percentage of defective beads that are allowed for premix and drop on glass beads according to EN 1423 [7] and EN 1424 [5], indicating that the methods are sufficiently gentle on the material to allow for recycling. Microscopy reveals that MM and WB4 contains a significant portion of glass beads (Fig. 4), 500—800 μm in size, while WB8 contains only few glass beads. WB8 contains fractions of glass grains, approximately 100—300 μm in size, typical for the type of anti-skid aggregates that are mixed with drop on beads and sprinkled on the road markings at application to fulfil initial requirements on retroreflection and skid resistance. Moreover, a substantial proportion of the glass beads exhibited irregular shapes, appearing more elongated or hourglass-shaped rather than round. Additionally, some beads contained air inclusions, surface irregularities, and cracks. In WB6, no glass beads were detected. Glass beads come in different qualities, and their roundness is measured and classified according to standard EN 1423 and EN 1424. Wenzel et al. [41] state that a standard batch of glass beads made from recycled glass should achieve a normative roundness of > 80 % and exhibit significantly lower roundness than glass beads of premium quality (often made from virgin raw materials). However, premium glass beads are seldom used due to the significantly higher cost [33,4]. It can be assumed that standard glass beads were used in the road marking materials in this study. Furthermore, the authors in Wenzel et al. [41] examined glass beads after wear tests and found that they exhibited visible surface deterioration. That type of deformity was not detected in the present study, suggesting that abrasive wear does not occur as a result of water blasting (WB) or mechanical milling (MM). Other types of defects, such as irregular shapes (tears and ovals) or different types of fused beads, satellites, and beads with gas inclusions are unlikely to arise during the recycling process. Milkiness or opaqueness could arise, but no such bead defects were found in this study. In summary, it can be concluded that there is no evidence for any performance reduction of the glass beads in the recycled thermoplastic road marking materials. However, since no evaluation of the retroreflective properties of the recycled raw materials has been carried out, any such claims remain uncertain and require further investigation. (Fig. 5)

The particle size distribution confirmed that the material collected with mechanical milling was coarser than the material collected with water blasting. Specifically, 40 % of the MM-collected material was finer than 2 mm, compared to 70–90 % for the WB materials

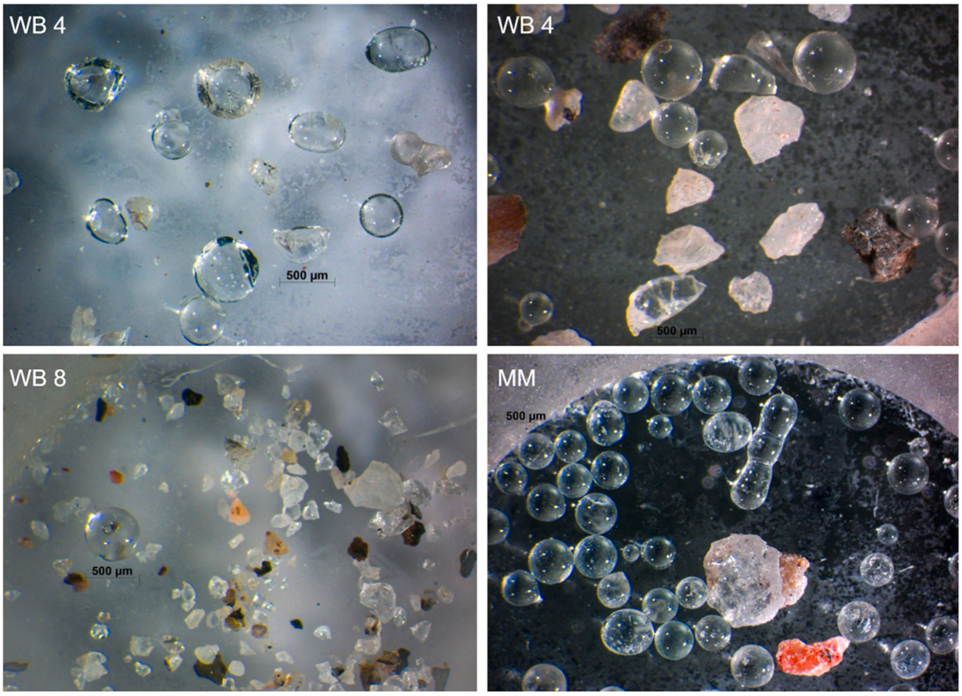

Fig. 4. Microscopy images of glass beads from WB4 (top row), WB8 (bottom left) and MM (bottom right). Note that the opaque, non-spherical particles visible in the images are anti-skid aggregates.

and approximately 15 % of the MM material was coarser than 16 mm. For the WB materials, only a small fraction of the particles was coarser than 2 mm, making it challenging to effectively separate road marking material from sand, silt, clay, and road dust. This could pose difficulties for large-scale recycling efforts. An excessive presence of silt and clay in the recycled material may adversely affect the color and overall quality of the newly produced road markings, especially if the material is also mixed with fine bitumen parts that will dissolve in the thermoplastic binder.

A granulometric analysis of the MM material revealed that thermoplastic constituted 48–54 % of materials exceeding 10 mm in size, 27–32 % within the 8 mm fraction, 30 % within the 4 mm fraction, and 11–12 % within the 2 mm fraction. The remaining material in each sieve fraction consisted of gravel, sand, and asphalt residues. These findings suggest that future research should prioritize improvement of the recycling processes to avoid removing unnecessary asphalt, but also to focus the recycling efforts on particle fractions larger than 10 mm, as they may be the most cost-effective to separate from residual materials. Additionally, materials down to 4 mm in size could also be considered for recycling; however, their efficient separation would require more advanced and effective methods.

3.2. *Laboratory analysis of recycled materials*

The complex structure of thermoplastic road marking materials is one of the reasons why it is not possible to evaluate the performance fully by laboratory testing. Laboratory testing used to be the basis of the certification of thermoplastic road marking materials in the Nordic countries, but the method was abandoned in favor of road trials.

The performance of thermoplastic road markings is influenced by the individual components of the material – the binder, the fillers, the pigments, the premix glass beads, and the additives. The type and exact amount must be adjusted for the actual climate conditions in the region where the material will be used, but it must also be adjusted to the type of application equipment. For use in harsh conditions with a significant proportion of vehicles with studded tires and in a climate that requires frequent winter road maintenance, the use of softeners in the form of polymers is crucial for the performance. Also, the viscosity of the material must be tuned to allow good flow in the application equipment, while the thixotropy is affecting the dimensional stability of the material.

The binder content (including all organic components, also additives such as polymers and oils) of thermoplastic road marking materials are normally around 20 % [32]. In the recycled materials, the binder content varies between $\bar{x}$ 7.8 % and $\bar{x}$ 21.7 % for WB materials and $\bar{x}$ 16.7 % for the MM material. The variation among the WB materials is large, however, for these materials, no separation of residual material (e.g., sand, clay, and road dust) and road marking material were made prior to the analysis. The analysis of the MM material was carried out on selected larger pieces of material that was possible to separate from gravel, sand, and road dust.

The low binder contents, most significant for WB1, WB3, and WB5, could influence the formulation of new materials incorporating recycled components. The binder content, as well as the *type* of binder if the recycled material is of unknown origin, are parameters that must be verified as a part of a quality assessment allowing the manufacturer to correctly compensate for reduced binder levels and ensure that the required performance is maintained.

For the MM material, a compositional comparison with the thermoplastic reference material is particularly relevant as both correspond to the same product. The slightly lower binder content compared to the product specification (see Table 4) is expected, since it was not possible to fully remove all road dust and traces of bitumen from the material in the recycling process. For WB materials, their origin and type of road marking material are unknown. Most WB materials contain large amounts of residues that influence the relative binder content since the materials were not separated from residues in the recycling process. However, for WB6 and WB8, the binder content is unexpectedly high, suggesting that those materials might be road marking paint rather than

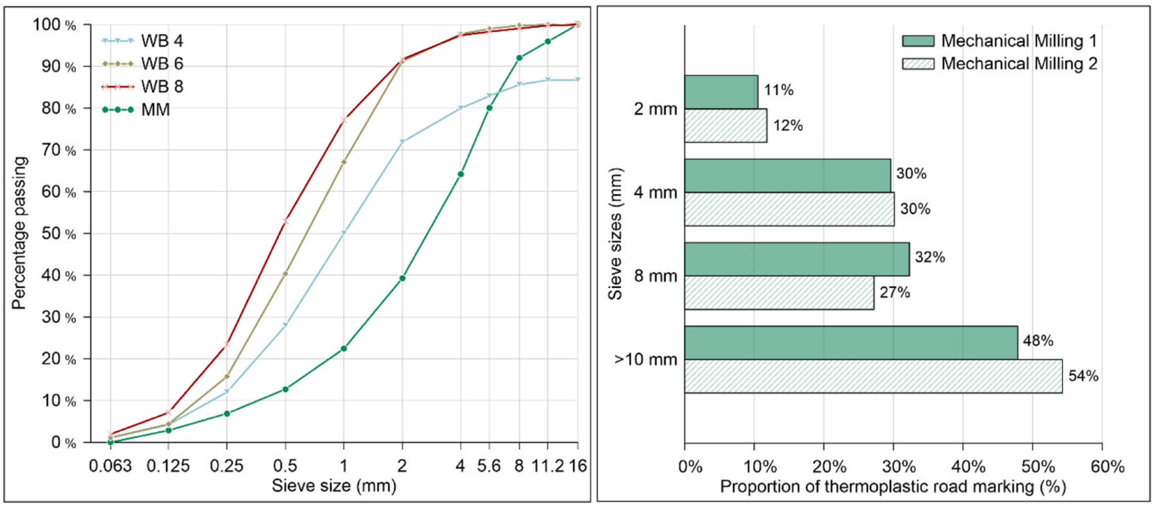

Fig. 5. Mean particle size distribution of MM, WB4, WB6, and WB8 (left) and proportion of thermoplastic road marking material in MM subsamples retained on sieves from 2 to > 10 mm (right).

thermoplastic materials. This is further supported by the low number of glass beads in WB8, the few glass beads and glass grains that can be detected in the premix could originate from drop on materials and anti-skid aggregates. However, since the binder type was not investigated, it cannot be definitely confirmed that WB 6 and WB 8 consist of road marking paint.

The TiO_2 content is a crucial parameter for obtaining both the white color and brightness of the material, but it also acts as an enhancer of the retroreflective properties of the glass beads in the road marking [34], which is one of the most important functions, providing visibility at night. TiO_2 contents as high as 10 % are sometimes reported in literature [28,4], but for Nordic conditions, white thermoplastic road marking materials rarely contain more than 4—6 % TiO_2 (NordicCert, unpublished information based on Manufacturer's Declaration of Constituents).

For WB materials, the TiO_2 content was determined for WB4, WB6 and WB8, and values range from 3.18—7.87 %. Since the WB road marking materials were not separated from residues, the relative concentrations are affected by the amount of residue in each sample. To estimate the amount of actual road marking in the recycled material, both the binder content and the TiO_2 content must be considered. Comparing WB4 and WB8 shows that both the binder content and the TiO_2 content is about twice as high for WB8 than for WB4 (21.7 % vs. 11.7 % and 7.87 % vs. 3.18 %), while the premix content is less than half (29.2 % vs. 69.0 %). The differences between WB8 and WB4 suggest that WB8 contains more road marking material, which is also supported by the higher luminance factor (a measure of the brightness of the material).

WB6 is similar to WB8 with respect to the binder content and the TiO_2 content (22.8 % vs. 21.7 % and 7.37 % vs. 7.87 %), but the premix content is about half, 12.5 % compared to 29.2 %. WB6 has the highest binder content of all recycled materials, but the lowest premix content. The TiO_2 content is high, which in conclusion suggests that WB6 contains large amounts of road marking. Microscopy shows no glass beads, which is not surprising since the premix content is very low. WB6 might also consist of water-based road marking paint. For MM, the TiO_2 and premix contents are also in line with what is expected from the product specification (Table 4).

The color, including the luminance factor β, and (x,y) chromaticity coordinates of the recycled materials, were determined as described above, and are presented in Table 3 (luminance factor) and in Fig. 6. The (x,y) chromaticity coordinates for two of the WB materials fall outside the chromaticity region (indicated by the black box in Fig. 6) for white road markings. WB5 is positioned significantly outside the allowed region, shifting towards the yellow side of the chromaticity diagram. This is expected, as most of the road marking material in this batch was yellow. However, WB5 is also outside the defined chromaticity region for yellow road markings (not shown), indicating that the road marking material content in WB5 is low. WB1 is positioned slightly outside the white box, towards the orange side of the chromaticity diagram. Although WB1 is a white material, it has the lowest luminance factor among all recycled materials (β=0.05) and one of the lowest binder contents (7.8 %) suggesting that the proportion of road marking material in WB1 is very low. Consequently, its chromaticity coordinates may have been influenced by other components such as bitumen, clay, silt, and sand. In contrast, WB2–WB8 (excluding WB5) and MM are clustered relatively closely together, all falling well within the chromaticity region for white road markings. The luminance factor of the MM material (β = 0.53) is significantly higher than for the WB materials, however, this can be attributed to the fact that the measurement was carried out on relatively clean flakes of pure MM material.

3.3. *Formulations with recycled materials*

The (x,y) chromaticity coordinates of formulations of thermoplastic road markings incorporating recycled materials are shown in Fig. 6 (right), with MM materials represented by squares and WB materials by triangles. A clear trend is observed, where increasing proportions of MM raw material in the formulations result in a color shift towards the yellow region of the chromaticity diagram (towards upper right). Concurrently, the luminance factor decreases from β = 0.69 to β = 0.63, and further to β = 0.54, as shown in Table 4. It is not surprising that the chromaticity coordinates of the formulations shift towards that of the recycled MM material with increasing content of recycled material, however, the rapid decrease in the luminance factor is unexpected. An addition of only 30 % recycled MM material causes a significant reduction in the brightness of the material.

The observed decrease in luminance factor with increasing levels of recycled material is most likely attributed to the presence of asphalt residue within the recycled MM material. This impurity, inherently darker and less reflective than the thermoplastic, likely reduces the overall reflectance of the material. While changes in TiO_2 dispersibility can influence optical properties, this mechanism is considered unlikely in the present case, as the overall composition and processing conditions of the formulation where the same for all recycling ratios. Therefore, the decline in luminance factor is primarily ascribed to residual asphalt particles, which are not fully removed in the recycling process.

For WB materials, the luminance factor is low (0.50—0.59) even with additions of only 10 % recycled material. The incorporation

Table 3
Summary of material properties for eight batches of recycled road marking material processed by water blasting (WB) and one processed by mechanical milling (MM).

Laboratory testing	WB1	WB2	WB3	WB4	WB5	WB6	WB7	WB8	MM
Binder content (%)*	*7.8*	*13.4*	*6.9*	*11.7*	*10.6*	*22.8*	*11.4*	*21.7*	*16.7*
TiO_2 content (%)	-	-	-	*3.18*	-	*7.37*	-	*7.87*	*5.48*
Premix content (%)*	*80.2*	*63.6*	*82.7*	*69.0*	*75.7*	*12.5*	*69.5*	*29.2*	*69.5*
Luminance factor,β**	*0.05*	*0.08*	*0.10*	*0.17*	*0.09*	*0.30*	*0.07*	*0.24*	*0.53*

*Average of 3 determinations. **Average of 10 determinations.

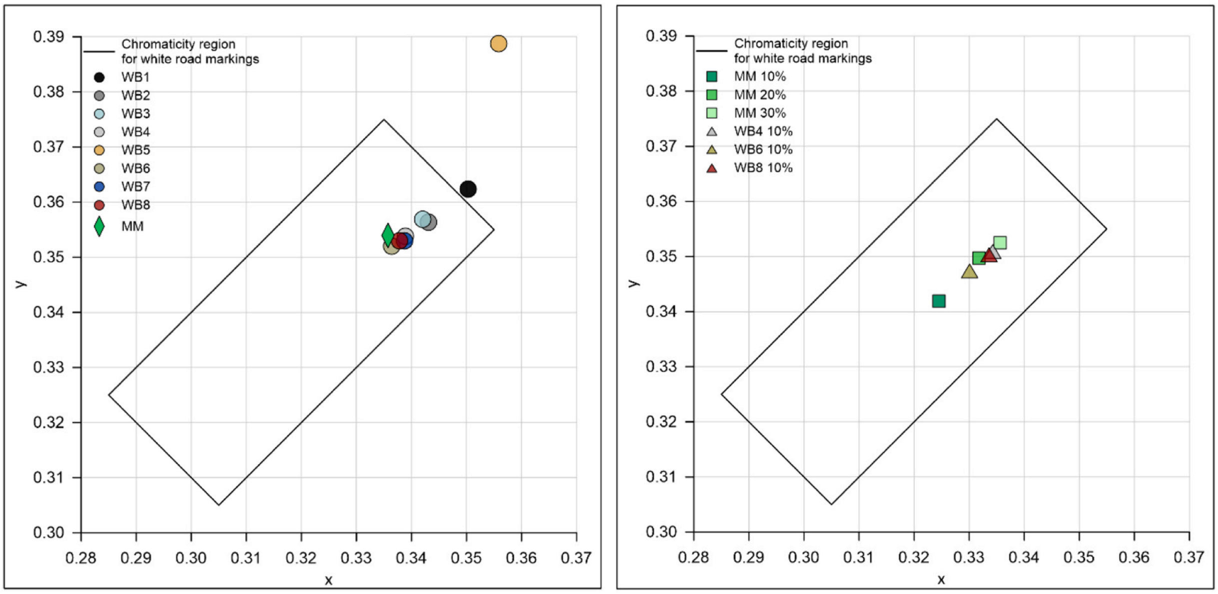

Fig. 6. Left: The (x,y) chromaticity coordinates for recovered raw materials (MM and WB1-WB8). Right: The (x,y) chromaticity coordinates for thermoplastic materials containing recycled material (MM 10 %, MM 20 %, MM 30 %, WB4 10 %, WB6 10 %, and WB8 10 %).

Table 4
Summary of material properties for reference and recycled road marking samples (WB=recycling by water blasting, MM= recycling by mechanical milling).

Laboratory testing	Reference material†	MM 10 %	MM 20 %	MM 30 %	WB4 10 %	WB6 10 %	WB8 10 %
Binder content (%)*	*18.9*	*19.7*	*21.0*	*18.4*	*17.7*	*19.1*	*19.1*
TiO_2 content (%)	*6.0*	*5.26*	*5.33*	*5.10*	*5.43*	*5.06*	*5.13*
Premix content (%)	*75.1*	-	-	-	-	-	-
Luminance factor,β**	*0.80*	*0.69*	*0.63*	*0.54*	*0.50*	*0.59*	*0.53*
Softening point (°C)***	*80*	*83*	*99*	*93*	*82*	*84*	*84*
Indentation value (s)****	*25*	*26*	*5*	*35*	*53*	*42*	*38*

† The material composition is taken from the product specification published in the EPD [14]. *Average of 3 determinations. **Average of 10 determinations. ***Average of 2 determinations. ****Average of 4 determinations.

of recycled materials may adversely affect R_L, color, and Q_d from the outset. Consequently, it is crucial to perform continuous monitoring and evaluation of these markings to ensure they meet performance parameters over time.

The luminance factor of thermoplastic road marking materials is divided into six classes according to EN 1871 [11]; LF1 and LF2 for yellow materials, and LF3-LF6 for white materials. The minimum requirement for white materials is $\beta \geq 0.65$ (LF3), which is only achieved by MM 10 %. The chromaticity coordinates for the formulations with 10 % WB4, 10 % WB6, and 10 % WB8, are shifted towards the blue region (lower left) compared to the corresponding chromaticity coordinates of the raw materials, owing to the large effect of the titanium dioxide (TiO_2) in the new formulations.

For the thermoplastic road marking formulations incorporating different types and proportions of recycled road marking material, the binder content was 19.7 %, 21.0 %, and 18.4 % for MM10 %-MM30 %, and 17.7 %, 19.1 %, and 19.1 % for 10 % WB4, 10 % WB6, and 10 % WB8, respectively. The MM raw material has a binder content of 18.4 %, as specified in the product specification. The binder content of MM 20 % is surprisingly high. The reason for this can be the sampling of MM 20 %, which was carried out after application at the road trials when only a little material was left in the boiler. Unfortunately, this can influence the material properties.

The TiO_2 content varied between 5.06 % and 5.43 %, compared to 6.0 % from the product specification of the reference material (Table 4). Comparing the titanium dioxide content in the formulations with the recycled raw materials give that even large variations in TiO_2 content in the raw materials give minor effects on the final TiO_2 content. This is not surprising since the additions of recycled materials are only in the range of 10—30 % and the TiO_2 content in the recovered raw materials were only approximately 3—8 % (Table 3).

The softening point is a measure of the temperature at which the thermoplastic material sample experiences deformation under the action of a 13.9 ± 0.1 g, Ø15 mm steel ball. The softening point for the reference thermoplastic material is approximately 80 °C, and formulations with 10 % recycled materials, WB4, WB6, WB8 and MM, show corresponding values (82–84 °C). For MM 30 % the value is slightly higher (93 °C), and for MM 20 % the value is even higher (99 °C). Softening point values are divided into five classes according to EN 1871 [11]; ranging from SP0 (no value requested) to SP4 (≥110 °C). All formulations fulfil class SP2 (≥80 °C), except

MM 20 % which is in class SP3 (≥95 °C).

Indentation is divided into six classes; from IN0 (no value requested) to IN5 (>20 min). Requirements for extrusion thermoplastic materials for Scandinavian conditions were previously IN1 (5–45 s), today there is no formal requirement. The reference value for the thermoplastic reference material is 25 s, and the other materials are in the range 5—42 s and thereby fulfill IN1, except WB4 10 %, which is in class IN2 (46 s to 2 min). However, the material that stands out compared to the others is MM 20 %, which has a significantly lower indentation values, 5 s, compared to the other ones. This supports the assumption that the sampling of MM 20 % has been carried out in a way that is not representative for the entire material formulation, and that it is expected that the material still demonstrates satisfactory function in the road trials.

3.4. Application at the road trials

The incorporation of recycled material into the formulations did not have a measurable impact on the viscosity or flowability during application in the road trials. A slight increase in heating time was observed compared to conventional thermoplastic road marking materials supplied in powder form. This was attributed to the block format of the recycled material, which required a longer melting time and marginally extended the preparation phase prior to application. No significant differences were observed between formulations with varying proportions of recycled content. Overall, the inclusion of recycled material did not negatively influence construction parameters essential for field performance.

3.5. Results from the initial measurements at the road trials

The thickness of the material was measured by a thickness gauge in at least 10 positions and also controlled by the weight of the material on the steel plate.

Initial performance measurements of the road marking materials applied at the road trials in September 2024 were carried out two weeks after the application. During the measurements, the weather was mostly cloudy with an air temperature and the road surface temperature around 15 °C. The evaluated parameters were the coefficient of retroreflected luminance R_L, the luminance coefficient under diffuse illumination Q_d, chromaticity coordinates (x,y), and anti-skid properties. The performance measurements of R_L, Q_d and chromaticity coordinates were carried out on absolutely dry markings. R_L and Q_d were measured using a handheld reflectometer. Measurements were taken at three points in a row within the measurement area defined by EN 1824 [12]. The results were calculated as the average of three measurements for each line.

Chromaticity coordinates were measured at one point on each line using a portable spectrophotometer with measurement geometry 45°/0°, 2° standard observer and standard light D65.

Anti-skid properties were evaluated by skid resistance measurements carried out using a *Portable Friction Tester version 4* (PFT), described in detail by [40], along the centre of each line. The results were calculated as an average of all measurements from one line, corresponding to approximately 70 measurements. The skid resistance was measured on wet markings. The measured values have been converted to SRT units.

The performance requirements for white type I markings is $R_L \geq 150$ mcd/m^2/lx, $Q_d \geq 130$ mcd/m^2/lx, skid resistance ≥ 50 SRT units, and chromaticity coordinates within the chromaticity region for white markings given in EN 1436 [10] (shown in Fig. 6).

Results from the initial measurements of MM 10 %, MM 20 %, and MM 30 % are presented in Table 5 and illustrated in Fig. 7. The yellowing of the materials with increasing MM content is observable with the naked eye and is most pronounced for MM 30 %. MM 30 % fails to meet the functional requirements, as the Q_d value of 111 mcd/m^2/lx is below the required threshold of 130 mcd/m^2/lx. In contrast, MM 10 % and MM 20 % satisfy all evaluated performance parameters. The initial testing shows that the materials containing 10 % and 20 % recycled MM content successfully passed all certification test, showing that incorporating 10—20 % recycled MM material, without additional preparation, in road markings applied in real traffic environments is feasible, with no adverse effects on functional performance. These early-stage results indicate that the inclusion of recycled content at these levels does not compromise the fundamental quality or compliance of the materials.

3.6. Environmental impact of recycling of thermoplastic road markings

This study serves as a proof-of-concept for the recovery and reuse of thermoplastic road marking materials, with emphasis on assessing technical viability rather than conducting a comprehensive environmental or economic evaluation. A life cycle assessment

Table 5
Results from the initial measurements at the NordicCert road trials in Norway 2024.

Performance parameter	MM 10 %	MM 20 %	MM 30 %
Coefficient of retroreflected luminance, R_L (mcd/m^2/lx)	224	214	200
Luminance coefficient under diffuse illumination, Q_d (mcd/m^2/lx)	144	135	111*
Skid resistance, μ (SRT units)	52	52	53
Material thickness [mm]	2.9	3.1	3.1
Color	OK	OK	OK

* Denotes a value that does not fulfil the requirements.

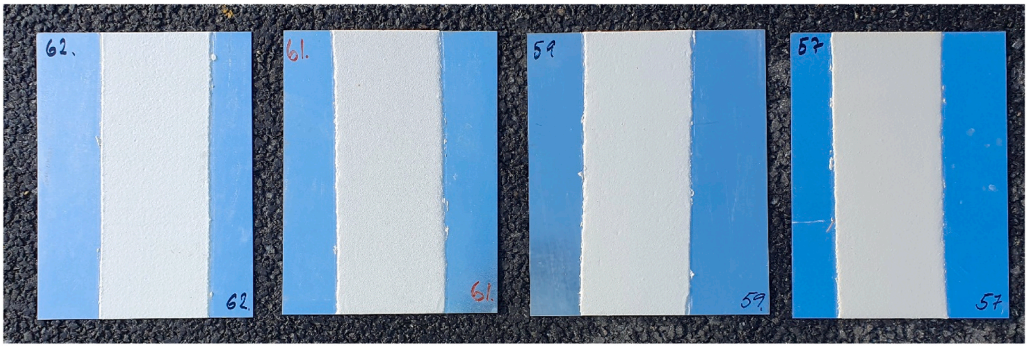

Fig. 7. A white reference material to the left, followed by MM 10 %, MM 20 %, and MM 30 %, applied on steel plates for thickness evaluation at the NordicCert road trials in Norway 2024.

(LCA) has not been performed, as it was beyond the scope of the study, since the absence of a large-scale recycling infrastructure currently limits the accuracy and relevance of such an analysis. Nonetheless, from a material substitution standpoint, a 1:1 replacement of virgin materials with recycled equivalents could theoretically yield proportional reductions in greenhouse gas emissions and resource consumption. It should be noted, however, that the recovery processes also require energy, as do subsequent necessary stages such as transport, particle separation, cleaning, etc. Despite these energy inputs, they are anticipated to be substantially lower than those associated with the production of virgin components, particularly fossil-derived binders, synthetic polymers, mining and processing of TiO_2, and the manufacturing of glass beads. Quantifying these trade-offs will require future LCA studies once a scalable and standardized recycling process is in place.

4. Conclusions

Recycling thermoplastic road marking materials presents both technical and economic challenges, primarily due to the material's complex composition, difficulty in removing contamination from asphalt residues of the recovered material, and the low cost of virgin raw materials, which diminishes the financial incentive for large-scale recycling.

This study compares high-pressure water blasting (WB) and mechanical milling (MM) for material recovery. WB caused less road surface damage but produced fine particles (70–90 % of particles $<$2 mm) that were difficult to separate from contaminants. Also, WB materials were of unknown origin and some batches most likely contained acrylic road marking paint which are fundamentally different in chemical composition compared to thermoplastic road marking materials, making them incompatible for mixing. MM yielded coarser particles, over 50 % of MM particles were $>$ 10 mm, making them easier to handle in a recycling process. Still, they contained significant asphalt contamination due to the mismatch between the milling drum width and the road marking width. To improve both removal and recycling efficiency, future efforts should focus on optimizing milling parameters such as width, depth, and vehicle speed to minimize the unintentional removal of asphalt.

Color properties, including the luminance factor and chromaticity coordinates, showed that most recycled samples met chromaticity requirements, with MM materials showing the highest luminance due to lower contamination. Binder content varied widely between samples, which could affect formulations with recycled components. Some WB samples had low binder levels, while others showed unexpectedly high binder levels, suggesting possible origin from road marking paint rather than thermoplastic materials. Accurate assessment of binder content and binder type will be critical for quality control of recycled materials to ensure consistent performance in new formulations.

Results from lab and the initial evaluation of the road markings applied in real traffic suggest that incorporating 10–20 % recycled material without pre-treatment is feasible and does not impair performance. However, long-term durability still needs to be monitored. The findings of this project demonstrate, for the first time, a promising and practical approach to advancing circular material use in the transportation sector.

CRediT authorship contribution statement

Hanna Fager: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Funding acquisition, Conceptualization. **Järlskog Ida:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Martin Gunnarsson:** Writing – review & editing, Validation, Resources, Investigation, Conceptualization. **Julia Danell:** Resources, Investigation, Conceptualization. **Niklas Aneklev:** Resources, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used chatGPT in order to improve and shorten some chapters of the manuscript as well as for a grammar check. After using this tool/service, the author(s) reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property. We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from hanna.fager@vti.se

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Data availability

Data will be made available on request.

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