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Sustainable Road Markings

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Synonyms

Glass beads; Machine vision; Renewal cycle; Retroreflectivity; Road safety; Service life

Definition

Road markings, which are ubiquitous road safety features, are a special type of industrial coatings that demand relatively frequent renewal to maintain properties. They are systems comprising a paint layer (providing color, adhesion to roadway, and surface for retroreflection) and a retroreflective layer (glass beads furnishing retroreflection and protecting the paint layer from abrasion). Sustainable road markings are those that afford the longest functional service life.

Function of Road Markings

Since introduction over a century ago, road markings (RM) became ubiquitous features on almost all roads; at present, no feasible alternative is known. RM are very effective and economical safety enhancers (Miller 1992); they inform the drivers about the boundaries of travel lanes and organize traffic. RM are necessary not only for human drivers; many machine vision sensors utilized in advanced driver assistance systems and the emerging technology of automated vehicles also rely on RM (Burghardt et al. 2020, 2021b). Despite the frequency of use, RM are very seldom considered *per se*, as a specific type of industrial coating, but are more likely to be treated as "just parts of the road" and are weakly described in scientific literature.

RM must be visible to drivers: it is achieved through contrast ratio (Brémond 2020). In the presence of ambient lighting, RM are visible only due to color (usually white, sometimes yellow, seldom other) providing contrast to the roadway surface; at night time, their visibility is augmented with retroreflectivity (measured as coefficient of retroreflected luminance, R_L). R_L is the key functional parameter of RM: based on the analysis of drivers' needs, recommended was R_L over 150 mcd/m^2/lx (Lee and Oh 2005). Because decrease in R_L signals the necessity of renewal (not replacement!), R_L is simultaneously the parameter controlling the functional service life of RM. Other functional parameters include daytime visibility (measured through luminance coefficient under diffuse illumination, Qd) and skid resistance (usually measured with British Pendulum Skid Resistance Tester that furnishes a unitless Pendulum Test Value). Literature related to the influence of RM and R_L on driver behavior was recently reviewed (Babić et al. 2020). The visual difference between RM with higher and lower R_L is shown in Fig. 1 (Burghardt et al. 2019b).

Sustainable Road Markings, Fig. 1 Pedestrian crossing at night, high R_L on the left and low R_L on the right (Burghardt et al. 2019b). (*Source*: Authors)

Materials for Road Markings

It is critical to understand that RM are systems comprising two distinct layers that must co-operate to provide the final functional coating. In all of the RM, the bottom paint layer provides the color and adhesion to the surface, while the top retroreflective layer with drop-on glass beads (GB) provides R_L and simultaneously protects the paint layer from abrasion. There are numerous materials that can be used for the paint layer (Babić et al. 2015), but only GB, sometimes mixed with anti-skid particles, are utilized for the retroreflective layer.

The following types of materials are commonly used for the paint layer: (1) solventborne paints – the oldest, easiest to manufacture, and still very commonly used; their disadvantage is the use of organic solvents, (2) waterborne paints – materials often used in some countries, more modern environmentally friendly type of paints capable of providing improved performance, (3) cold plastic – solventless material that forms film through free radical polymerization that takes place on the road surface, designed either with coarse fillers for extrusion application of thick layers (usually 1–5 mm) or without them for spraying at thin layers; hard and durable material not designed for slow wear, (4) thermoplastic – solventless material applied from a hot melt (approximately 200 °C), designed either with coarse fillers for extrusion application of thick layers (usually 1–5 mm) or without them for spraying at thin layers; relatively soft material designed for slow wear during usage; the binder can be polymeric or non-polymeric, (5) plural component systems – seldom used materials based usually on epoxy or urethane chemistry, available in solventborne, waterborne, or solventless versions, and (6) tapes – advanced modern structured material with all properties (including the drop-on glass beads) fixed during the manufacture, attached to the road surface with pressure-sensitive adhesive; prohibitively expensive, but capable of furnishing exceptional performance. Cold plastic and thermoplastic can be applied at thick layers in the form of regular or stochastic structures to provide vibroacoustic effect and to improve water drainage for augmented R_L under rainy conditions; upon loss of R_L, these materials are renewed with sprayed materials applied at wet films approximately 0.4 mm thick. All of these paint layer materials are reflectorized with a layer of GB with diameters 0.1–2.0 mm, dropped on immediately, while the paint layer materials are still liquid. These GB can be mixed with hard inorganic particles of similar dimensions to enhance skid resistance. Coating of the GB with an organosilane assures their good adhesion to the paints.

Ingredients of the paint layer are similar to those found in any other coatings: a binder forms film, pigments furnish color, fillers make the bulk of the coating, additives permit for processing and application, and all of them are suspended in solvents that can be a volatile organic compound (VOC), water, or can polymerize to become a part of the coating. Importantly, the majority of hazardous ingredients has already been eliminated from RM through various national specifications;

nonetheless, further regulatory curtailing of the remaining seldom used risky chemicals is envisaged as necessary for enhanced environmental and health protection.

The selection of solvents for RM paints is quite limited because of the requirements associated with drying and solubility parameters (Burghardt and Pashkevich 2021). Extensive discussion related to VOC in RM was recently published (Burghardt and Pashkevich 2018); to eliminate uncertainties associated with dissimilar definitions of VOC, it was proposed that instead of nominal VOC contents, Ozone Formation Potential based on Total Organic Gases should be used; additionally, the calculations should comprise a series of RM renewals to account for the functional service life (Burghardt and Pashkevich 2020). However, complete elimination of solvents should bring even more advantages – materials like cold plastic, which simultaneously were reported among RM furnishing the longest service life, could be used (Cruz et al. 2016; Burghardt et al. 2022a). Other solventless RM, including frequently used thermoplastic masses, high-end RM tapes, and plural component systems are also available. The second best solvent, water (Zhou et al. 2019), is used in another durable modern RM – waterborne paints.

Pigments and fillers can comprise even 70% of the paint layer. Any hazards associated with them can play a role only if the RM undergo abrasion, which under normal situation and with proper maintenance is unlikely because the paint layer is protected with a layer of GB (Burghardt et al. 2022c). Among pigments, one must first list titanium dioxide (TiO_2), which gives the white color and furnishes opacity; within the current technology the use of alternatives to TiO_2 could be associated with extremely high environmental burden (European Coatings TiO_2 Forum 2018). The recent negative publicity related to TiO_2 and the requirements for hazard labeling were criticized as not based on sound scientific assessment and possibly misleading (Riebeling et al. 2020). Lead chromate, a highly toxic inorganic pigment that was in the past frequently used in yellow RM, was for many years successfully replaced with readily available benign organic pigments that furnish very good performance without reported environmental or health hazards (Stratmann et al. 2020). The elimination of lead chromate and other harmful pigments occurred due to regulatory action.

Additives usually comprise less than 5% of the entire coating formulations; most of them are polymeric and have low environmental impact; despite occasionally reported hazards they are not worth deeper discussion herein. Additives like phthalates or alkylphenol ethoxylates are, based on professional knowledge, not needed in any modern formulations.

The majority of film forming binders in RM are polymeric, currently mostly acrylic, but alkyd, chlorinated rubber, vinyl, epoxy, urethane, urea, styrenic, and other materials can also be utilized. The polymeric binders and additives can be treated as potential sources of microplastic – an important emerging priority pollutant (Akdogan and Guven 2019). Only in the case of thermoplastic RM (note that the word *thermoplastic* does not fully correspond herein to its meaning in polymer chemistry, but indicates rather application from a hot melt), the binders can be non-polymeric; their status as contributing to microplastic is uncertain (Hartmann et al. 2019).

There is enormous chaos, inconsistency, and frequent errors in the literature related to the contribution of RM to the microplastic pollution (Burghardt et al. 2022c). In majority of publications complete or almost complete abrasion of the RM was assumed, which is not correct because of the renewal procedures: upon loss of R_L the RM are not replaced, but renewed with another layer of paint and glass beads – thus stacking of the layers occurs, as was found repeatedly in the field (Fig. 2). The renewal procedures and stacking of layers create a meaningful distinction between the functional service life (the loss of R_L) and the physical service life (the loss of RM themselves, which commences only after the end of functional service life, i.e., when the RM do not meet the statutory performance requirements).

Consequently, the reports estimating that RM could be responsible for approximately 7% of all secondary microplastics (Hann et al. 2018) are most likely overestimates by an order of magnitude and approximation of 0.7% seems more correct

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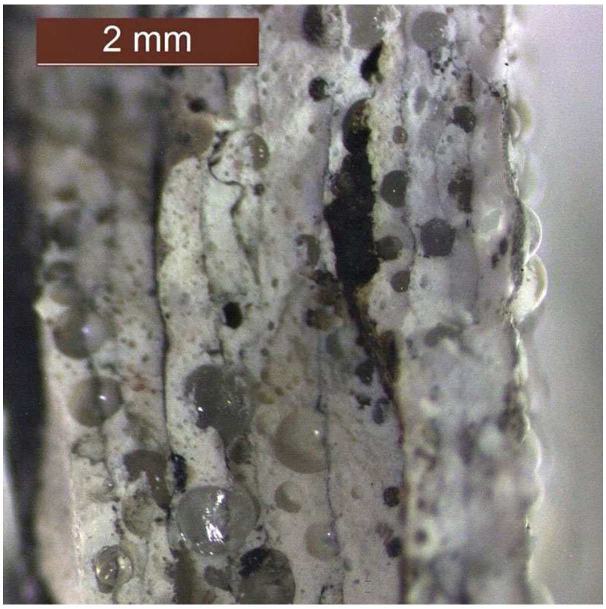

Sustainable Road Markings, Fig. 2 Cross-section of RM, visible numerous layers from renewals, with glass beads present at each layer (Burghardt et al. 2022c). (*Source*: Authors)

(Wang et al. 2019). So far, only very sparse positive identification of RM among plastic debris was reported and in most cases it was a thermoplastic material (Horton et al. 2017; Vijayan et al. 2022; Kitahara and Nakata 2020; Kang et al. 2022), while numerous studies of road dusts and road runoff fail to positively assign any found microplastic particles to RM (Liu et al. 2019; Polukarova et al. 2020; Roychand and Pramanik 2020).

Second inalienable and critical component of all RM are GB. They are usually prepared from recycled float glass; hence, they have refractive index (RI) 1.5. Reported was also manufacture from virgin raw materials, sometimes with ingredients added to improve surface quality and to increase RI. Such "premium" GB, with RI 1.6–1.7 were recently extensively studied because of high initial R_L that they provided and the associated prolongation of service life (Sitzabee et al. 2012; Burghardt et al. 2019a, b, 2021a, b). It should be noteworthy that GB with RI 1.9 did not furnish long service life, even though the initial properties were outstanding; this was explained by their low resistance to surface damage (Wenzel et al. 2022). The protective role of GB must be emphasized again – as long as the drop-on GB are present at the surface of RM, tires are rolling on them and are not touching the surface of paint layer; hence, abrasion occurs only after GB are lost, at which time RM are no longer a functional product because they lost the required R_L. The exacerbated abrasion by studded tires must be noted here; however, it is not a global, but local issue.

GB are not a hazardous material, but in the past, there was a risk of their contamination with toxic metals (dos Santos et al. 2013). It is absent nowadays because of various standards that effectively excluded contaminated materials from the market. Indeed, field measurements confirmed that (Migaszewski et al. 2021); also, confirmed was their fully annealed amorphous state, without any crystalline phase (Burghardt et al. 2022b).

Based on the present state of knowledge, essentially none of the emerging raw materials that could be utilized in RM are seen by the authors as feasible environmentally friendly solutions. Such skepticism is a result of the practical experience with RM and the knowledge of performance demands. Sustainability cannot be achieved with the use of materials that are not readily available or require extensive processing, like rare earths (McLellan et al. 2013), which eliminates at present some of the quite interesting novel concepts like thermochromic or luminescent RM (Nance and Sparks 2020). Incorporation of metallic particles within RM to facilitate their recognition by machine vision sensors was patented, but not otherwise explored. The RM ingredient that cannot be efficiently replaced with any currently known technology are GB.

Service Life – The Key Sustainability Parameter

RM are the least durable elements of road infrastructure – service life of 1–3 years was typically given in literature. Nonetheless, the usage of high-end materials and "premium" glass beads was reported to significantly increase the functional service life and thus to decrease the consumption of natural resources (Burghardt et al. 2022a). No universal formula for prediction of service life of RM was developed despite numerous attempts (Babić et al. 2019); apparently, the effect of environmental and abrasion factors (line location, weather, traffic load and type, activity of snow ploughs, use of studded tires, etc.) is enormous. It must be emphasized that the initial R_L should not be considered as a sufficient indicator for the service life of RM (Harun et al. 2019; Burghardt et al. 2021a).

After R_L drops below the level permitted by local regulations, usually 100 mcd/m^2/lx (despite the recommended minimum 150 mcd/m^2/lx), RM are not replaced but renewed with a paint layer and the drop-on GB layer. Because of differences in the length of service life of different materials, a series of renewals should be considered to assess the overall environmental impact instead of one-time event of application. Two independently prepared cradle-to-grave Life Cycle Assessments confirmed that the choice of materials for RM played only minor secondary role as compared to the service life they afford (Cruz et al. 2016; Burghardt et al. 2016), which concurs with correlating sustainability of products with their service life. The use of functional service life parameter for sustainability assessment was possible and reasonably accurate in case of RM because of the aforementioned almost complete elimination of really hazardous materials from them. Accordingly, methodology to quickly evaluate the usage of raw materials for RM has been developed and its utility demonstrated based on results from field studies (Burghardt and Pashkevich 2020, 2021).

Outlook

Based on long-term consumption of resources to maintain RM within the functional specifications, most sustainable are those that furnish longest service life.

Besides the few undesired ingredients that require regulatory intervention, analyses have demonstrated that the use of RM furnishing longest service life was simultaneously bringing long-term financial benefits (Burghardt and Pashkevich 2020), so the less environmentally friendly solutions could be eliminated by simple employment of the free market economy. However, this can be successful only with long-term performance contracts and the freedom of materials choice given to the RM applicators – excessive compositional restrictions, like those currently employed in North America, were reported as hindering development and introduction of novel, more effective solutions (Burghardt et al. 2022a).

The main purpose of installation of RM – road safety – must never be forgotten. Constant increase in performance requirements, to match the specifications with the advanced current technologies, may be the easiest method for promotion of constant development and further improvements. Simultaneously, overengineering and unrealistic demands must be avoided. Cooperation between all of the stakeholders and understanding the needs and capabilities by all of the involved parties appears crucial for success and for safe driving at well-marked roads.

Cross-References

▶ Bioeconomy and Green Plastic Production
▶ Environmental Benign Green Materials, Synthesis and Applications
▶ LCA Applications Addressed to Green Materials
▶ Polymeric Material from Plant Oil and Their Application

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Sustainable Technology

► Green Extraction Technology for Plant-Based Natural Products
► Green Materials for Biosensor Development

Synthesis

► Green Membrane Preparation and Manufacturing Practices

Synthesis and Characterization of Nanocatalyst for Production of Biodiesel

► Nanocatalyst for Production of Biodiesel

Synthesis of Biomimetic Hydroxyapatite from Natural Sources for Bone Tissue Engineering

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Abbreviations

3D	Three-dimensional
ALP	Alkaline phosphate
BTE	Bone tissue engineering
ECM	Extracellular matrix
GO	Graphene oxide
HAp	Hydroxyapatite
MC	Methylcellulose
MTT	(3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide)
NP	Nanoparticle
PET	Polyethylene terephthalate
PU	Polyurethane
PVA	Polyvinyl alcohol
SBF	Simulated body fluid

S