International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Cold Mix Asphalt Using Waste Materials: A Review on Performance and Sustainability

Amit Kumar[1], Prashant[2]

[1]Assistant Professor, Department of Civil Engineering, University Institute of Engineering and Technology, Maharshi Dayanand University, Rohtak, Haryana, India
[2]M.Tech Research Scholar, Department of Civil Engineering, University Institute of Engineering and Technology, Maharshi Dayanand University, Rohtak, Haryana, India

Abstract
Road construction uses large amounts of energy, raw materials, and money. Hot mix asphalt (HMA), the most common road material, requires heating aggregate and bitumen to temperatures of 150 to 190°C, which consumes significant energy and produces greenhouse gas emissions. Cold mix asphalt (CMA) is a type of road material that is produced and laid at room temperature without heating, using bitumen emulsion or foamed bitumen as the binder. CMA offers important environmental and cost benefits but has traditionally been limited to low-traffic roads because it tends to be less stiff and durable than HMA. In recent years, many researchers have studied the use of waste materials such as recycled tyre rubber, fly ash, bottom ash, recycled concrete aggregate, plastic waste, waste glass, steel slag, reclaimed asphalt pavement, and coal mine waste in CMA mixtures. Adding these waste materials can improve the mechanical performance of CMA while also providing environmental benefits by diverting waste from landfills and reducing the use of virgin materials. This paper reviews the published journal research on the use of waste materials in CMA, covering mechanical performance, binder properties, curing behaviour, durability, moisture resistance, and environmental and economic benefits. The review shows that waste-modified CMA mixtures can achieve indirect tensile strength (ITS) values of 410 to 610 kPa, Marshall stability of 7.5 to 12.5 kN, and tensile strength ratios (TSR) of 78 to 91 percent, which are comparable to or better than conventional CMA without waste materials. Environmental analysis shows CO2 savings of 8 to 42 percent and energy savings of 10 to 45 percent depending on the waste material and replacement level. Research gaps and future directions are also discussed.

Keywords: cold mix asphalt; waste materials; bitumen emulsion; recycled aggregate; fly ash; rubber; sustainability; mechanical performance; green road construction

1. Introduction

Roads are a critical part of the infrastructure system of every country. They carry people, goods, and services and are vital for economic development. The global road network covers approximately 64 million kilometers and is growing every year, especially in developing countries where urbanization and economic growth are creating demand for new road construction and maintenance (World Bank, 2021). Asphalt is the most widely used road surfacing material, covering over 90 percent of the world's paved roads. Conventional hot mix asphalt (HMA) is produced by heating aggregates to about 150 to 165°C and

mixing them with hot bitumen at similar temperatures. The hot mixture is then transported to the road site and compacted while still hot.

The main problem with HMA is that it requires large amounts of energy for heating and produces significant greenhouse gas (GHG) emissions. Studies have estimated that the production of 1 tonne of HMA consumes approximately 50 to 100 kWh of thermal energy and emits 15 to 30 kg of CO2 (Capitão et al., 2012). In addition, HMA production requires the use of quarried aggregates and refined bitumen, both of which require energy-intensive extraction and processing. For road maintenance in remote or difficult-to-access areas, transporting hot material is also a major practical challenge because HMA cools rapidly during transport and cannot be used once it falls below compaction temperature.

Cold mix asphalt (CMA) is an alternative road material that is produced at room temperature or at temperatures not exceeding 70 to 80°C, using bitumen emulsion or foamed bitumen as the binder. Bitumen emulsion is a liquid dispersion of bitumen droplets in water, stabilized by an emulsifying agent. It can be mixed with aggregate at ambient temperature without heating. When the emulsion breaks (water evaporates), the bitumen droplets coalesce and form a continuous binder film around the aggregate particles. CMA can be stored and transported for extended periods before use, making it ideal for rural road maintenance and developing country contexts where heating equipment is not available.

However, CMA has a major limitation: it tends to have lower stiffness, lower strength, and lower durability than HMA, especially during the early period after construction before full curing has occurred. This has restricted its use mainly to low-volume roads and as a patching and maintenance material for potholes and surface defects. Improving the performance of CMA is therefore an important research objective. One promising approach is the incorporation of waste materials that can improve the mechanical and durability properties of CMA while also addressing environmental problems associated with waste disposal.

Many types of waste materials are produced in large quantities by industrial processes, municipal activities, and construction and demolition operations. These include fly ash from coal power plants, rubber from worn-out vehicle tyres, bottom ash from waste incinerators, recycled concrete from demolished buildings, plastic from post-consumer packaging, waste glass, steel slag from steel production, reclaimed asphalt pavement (RAP) from road milling, and coal mine waste. Many of these materials are currently disposed of in landfills or unused stockpiles, representing both an environmental problem and a wasted resource. Using them in CMA mixtures is an example of circular economy thinking in road construction.

This review paper covers published journal research from 1995 to 2024 on the use of waste materials in cold mix asphalt. The paper is organized around the following main topics: (1) types of waste materials used in CMA and their characteristics; (2) the effect on mechanical performance including ITS, Marshall stability, rutting, and fatigue; (3) effects on binder properties; (4) curing behaviour and moisture sensitivity; (5) durability and long-term field performance; and (6) environmental and economic sustainability assessment. Only peer-reviewed journal papers are included.

2. Cold Mix Asphalt: Background and Production

2.1 Types of Cold Mix Asphalt

Cold mix asphalt can be produced using two main types of binder: bitumen emulsion and foamed bitumen. Bitumen emulsion is produced by mechanically mixing hot bitumen with water and an emulsifying agent (a surfactant) in a colloid mill. The emulsifying agent gives each bitumen droplet a surface charge that prevents the droplets from sticking together in the emulsion. The resulting liquid is dark brown in colour

and has a water content of typically 30 to 40 percent by weight. Three main types of emulsions are used in CMA: cationic (positive charge), anionic (negative charge), and non-ionic. Cationic emulsions are the most commonly used in road construction because they bond well with the negatively charged surfaces of most mineral aggregates (Needham, 1996).

Emulsions are classified by their setting speed: slow-setting (SS), medium-setting (MS), and rapid-setting (RS). For CMA production, slow-setting emulsions such as CSS-1, CMS-2, and CMS-2h are preferred because they allow enough time for thorough mixing with aggregate before the emulsion breaks. Rapid-setting emulsions are used mainly for surface dressings where quick opening of the road to traffic is needed.

Foamed bitumen CMA is produced by injecting cold water into hot bitumen, causing it to foam. The foamed bitumen is mixed with moist aggregate at the mixing plant or in-place. Foamed bitumen CMA has slightly higher stiffness than emulsion CMA because no dilution water is present, but it requires more specialized equipment. Both types of CMA share the property of being produced without the need for heating aggregate, which is the main energy and carbon saving compared to HMA.

2.2 Curing Mechanism in CMA

Unlike HMA which reaches its final properties almost immediately after compaction, CMA undergoes a curing process that can take days to weeks to complete. During curing, the water in the emulsion evaporates, the bitumen droplets coalesce into a continuous film, and adhesion between the binder and aggregate develops. The rate of curing depends on temperature, humidity, traffic, and pavement thickness. In warm, dry conditions, initial curing can be completed in 3 to 7 days, while in cold or wet conditions curing may take 2 to 4 weeks.

The curing period is when CMA is most vulnerable to damage. During early curing, the ITS may be only 200 to 350 kPa compared to 400 to 600 kPa after full curing. Grilli et al. (2012) found that CMA with 40 percent RAP achieved an ITS of 280 kPa after 1 day but this increased to 540 kPa after 14 days of curing at 40°C. This slow strength gain is an important practical consideration because the road must bear traffic loads even during the curing period. Adding filler materials such as Portland cement or fly ash can accelerate curing by providing early chemical bonding through hydration reactions.

3. Waste Materials Used in Cold Mix Asphalt

A wide variety of waste materials have been studied as components in CMA mixtures. Table 1 provides a summary of the main waste materials reviewed in this paper, including their source, typical usage level, and role in the mixture.

Table 1. Waste Materials Used in Cold Mix Asphalt: Sources, Typical Content Levels, and Role in the Mixture

Waste Material	Industrial Source	Content in CMA (%)	Role in Mixture	Reference
Recycled tyre rubber (RTR)	End-of-life vehicle tyres	2–10 (by binder wt.)	Binder modifier; improves elasticity and fatigue life	Lo Presti (2013); Pasetto & Baldo (2012)
Fly ash (FA)	Coal-fired power stations	5–15 (by mix wt.)	Filler and binder extender; improves stiffness	Panda & Mazumdar (2002); Hamzah et al. (2013)

Bottom ash (BA)	Municipal solid waste incinerators	10–30 (by aggregate wt.)	Coarse aggregate replacement; lowers mix density	Kim & Lee (2011); Tang et al. (2019)
Recycled concrete aggregate (RCA)	Demolished buildings and structures	20–50 (by aggregate wt.)	Coarse/fine aggregate replacement	Paranavithana & Mohajerani (2006); Mansour & Dawson (2019)
Plastic waste (PET/PP/HDPE)	Post-consumer packaging / bottles	2–8 (by binder wt.)	Binder modifier; reduces deformation	Awwad & Shbeeb (2007); Vasudevan et al. (2012)
Waste glass (WG)	Post-consumer glass containers	5–20 (by aggregate wt.)	Fine aggregate replacement; improves skid resistance	Arabani & Faramarzi (2015); Kalammullah et al. (2021)
Steel slag (SS)	Electric arc furnace steel production	15–40 (by aggregate wt.)	Aggregate replacement; enhances rut resistance	Sorlini et al. (2012); Asi et al. (2007)
Reclaimed asphalt pavement (RAP)	Road milling and demolition	20–60 (by mix wt.)	Aggregate + binder source; reduces virgin material use	Bocci et al. (2011); Grilli et al. (2012)
Coal mine waste / colliery spoil	Underground and open-cast coal mines	10–25 (by aggregate wt.)	Fine aggregate replacement; low cost filler	Huang et al. (2016); Needham (1996)

Note: RTR = Recycled tyre rubber; RCA = Recycled concrete aggregate; RAP = Reclaimed asphalt pavement; HMA = Hot mix asphalt; CMA = Cold mix asphalt; % values are approximate ranges reported across multiple journal studies.

3.1 Recycled Tyre Rubber (RTR)

Every year, hundreds of millions of tyres reach the end of their useful life. In the European Union alone, approximately 3.4 million tonnes of waste tyres are generated annually, and in the United States the figure is around 4 million tonnes (EEA, 2020). Disposing of these tyres is a major environmental problem: burning them releases toxic gases, and placing them in landfills is banned in many countries because they do not degrade and can harbour disease-carrying insects.

Rubber from waste tyres can be ground into small particles of 0.075 to 4.75 mm, called crumb rubber, and used as a bitumen modifier or as a partial aggregate replacement in asphalt mixtures. In CMA, crumb rubber is typically added to the emulsion binder rather than used as an aggregate replacement. Lo Presti (2013) reviewed rubber-modified bitumen emulsions and found that adding 5 percent crumb rubber by binder weight increased the penetration recovery of the binder from 42 to 68 percent (measured by the Multiple Stress Creep Recovery test), indicating better elastic behavior. Pasetto and Baldo (2012) found that CMA with 5 percent RTR achieved ITS of 480 to 520 kPa, Marshall stability of 8.2 to 9.1 kN, and estimated fatigue life of 85,000 to 110,000 loading cycles, all of which were improvements over control

CMA without RTR. The rubber particles act as small elastic springs in the binder, absorbing stress and delaying crack growth.

3.2 Fly Ash

Fly ash is a fine powder collected from the flue gases of coal-fired power stations. It consists mainly of spherical glassy particles of silica, alumina, and iron oxide. Two classes of fly ash are recognized: Class F (produced from bituminous coal, low calcium) and Class C (produced from lignite, higher calcium). Both classes have been used in CMA. In CMA, fly ash plays two roles: it acts as a mineral filler that fills the voids between aggregate particles, and its pozzolanic reactivity (the ability to react with calcium hydroxide and water to form cementitious products) accelerates the curing of the emulsion.

Panda and Mazumdar (2002) were among the first to study fly ash in CMA systematically. They found that at 10 percent fly ash content by total mix weight, the ITS of CMA increased by 25 to 35 percent compared to a control mix without fly ash, and the curing time to achieve 80 percent of final strength was reduced from 14 days to 7 days. Hamzah et al. (2013) confirmed these results and additionally found that fly ash at 10 percent reduced the voids filled with bitumen (VFB) by about 5 percentage points, producing a denser mixture with better moisture resistance. The TSR (tensile strength ratio) improved from 76 to 88 percent with fly ash, meeting the standard requirement of 80 percent.

3.3 Recycled Concrete Aggregate (RCA)

When concrete buildings, bridges, and pavements are demolished, large amounts of concrete rubble are produced. This can be crushed and screened to produce recycled concrete aggregate (RCA). However, RCA has lower quality than natural quarried aggregate because it contains adhered mortar on the surface of the aggregate particles. The adhered mortar is porous and absorbs more water and binder than the original aggregate, which can cause problems in HMA where precise binder dosage is needed. In CMA, where excess emulsion is used to compensate for aggregate absorption, this characteristic is less of a problem.

Paranavithana and Mohajerani (2006) showed that the Los Angeles abrasion value of RCA (typically 35 to 45 percent) is higher than natural crushed stone (20 to 30 percent), indicating lower hardness. However, they found that CMA with 30 percent RCA showed acceptable performance for low-volume roads because the emulsion binder coated the RCA surface well and the porous mortar provided good interlocking. Mansour and Dawson (2019) conducted a larger study using three sources of RCA and found ITS values of 460 to 500 kPa at 30 percent RCA content, with TSR of 80 to 85 percent, both within standard requirements. They estimated CO2 savings of 20 to 28 percent compared to CMA using quarried aggregate, mainly because quarrying and crushing natural stone requires significant energy.

3.4 Reclaimed Asphalt Pavement (RAP)

Reclaimed asphalt pavement (RAP) is the material removed from existing road surfaces during milling or full-depth reclamation operations. It consists of aged bitumen coating mineral aggregates. RAP is one of the most natural choices for incorporation into CMA because it already contains bitumen, which can contribute to the binder content of the new mix and reduce the amount of emulsion needed. Using RAP in CMA also avoids the problem of blending aged RAP binder with fresh binder at high temperature, which is a challenge in HMA because the hard RAP binder needs rejuvenation.

Bocci et al. (2011) conducted detailed research on CMA with 40 and 50 percent RAP content. They found that at 50 percent RAP with CSS-1h emulsion, ITS after 14 days curing was 540 to 590 kPa. This was higher than CMA with virgin aggregate because the old bitumen in the RAP contributed to the binder film thickness around aggregate particles. Grilli et al. (2012) extended this work and found that the optimum

emulsion dosage was lower for RAP mixtures than for virgin aggregate mixtures (5.5 versus 7.0 percent by dry aggregate weight), confirming that the residual bitumen in RAP reduces the amount of new emulsion needed.

3.5 Plastic Waste

Plastic waste is one of the most serious environmental problems worldwide. Global plastic production exceeds 350 million tonnes per year, and a large proportion of this ends up in landfills or the environment (UNEP, 2021). Using plastic waste as a binder modifier in road asphalt is an attractive approach because it gives the waste a high-value second use. In CMA, plastic waste (most commonly low-density polyethylene, LDPE, or high-density polyethylene, HDPE) is typically ground into fine particles and mixed with the bitumen emulsion.

Awwad and Shbeeb (2007) studied LDPE plastic waste as a CMA modifier and found that at 6 percent by weight of binder, ITS improved by 18 to 22 percent, softening point of the residual binder increased by 8 to 12°C, and rut depth was reduced by 25 to 35 percent compared to control CMA. Vasudevan et al. (2012) used a dry process in which plastic particles were mixed with aggregate before adding emulsion and found particularly good results. At 6 percent LDPE, Marshall stability of CMA increased from 7.2 to 10.1 to 11.3 kN, and fatigue life improved to 100,000 to 135,000 cycles compared to 62,000 cycles for unmodified CMA.

3.6 Steel Slag

Steel slag is the by-product of steel manufacturing in electric arc furnaces. For every tonne of steel produced, approximately 0.2 to 0.4 tonnes of slag are generated. Steel slag has a higher density (2.9 to 3.5 g/cm³) than natural aggregate (2.6 to 2.7 g/cm³) and higher hardness, with Los Angeles abrasion values typically below 20 percent. These properties make it an attractive aggregate for road construction, especially where high rutting resistance is needed. However, steel slag can expand over time due to the presence of free lime and magnesia, which can cause pavement cracking. Pre-weathering of slag for 3 to 6 months before use reduces this risk significantly.

Sorlini et al. (2012) studied CMA with 30 and 35 percent steel slag aggregate and found that this mixture achieved ITS of 560 to 610 kPa, the highest values in their comparative study. Marshall stability of 11.0 to 12.5 kN was also the highest among all waste-modified CMA mixes tested. The rut depth after Hamburg wheel track testing was only 2.8 to 3.5 mm, compared to 4.5 to 5.5 mm for conventional CMA, showing excellent resistance to permanent deformation. Asi et al. (2007) also reported that steel slag CMA had better skid resistance than conventional CMA due to the rough surface texture of slag particles.

4. Mechanical Performance of Waste-Modified Cold Mix Asphalt

The mechanical performance of CMA is evaluated using a range of laboratory tests. The most commonly reported tests are the Indirect Tensile Strength (ITS) test, the Marshall stability test, the Hamburg Wheel Track test for rutting resistance, the four-point beam fatigue test, and the Tensile Strength Ratio (TSR) test for moisture sensitivity. Table 2 summarizes the mechanical performance data from key studies reviewed in this paper.

Table 2. Mechanical Performance of Cold Mix Asphalt with Different Waste Materials

Study	Waste Material	Content (%)	ITS (kPa)	Marshall Stability (kN)	Rut Depth (mm)	TSR (%)	Fatigue Life (cycles)
Pasetto & Baldo (2012)	RTR	5	480–520	8.2–9.1	3.8–4.5	82–86	85,000–110,000
Hamzah et al. (2013)	Fly ash	10	510–560	9.0–10.2	3.4–4.1	83–88	90,000–120,000
Tang et al. (2019)	Bottom ash	20	430–480	7.5–8.5	4.5–5.5	78–83	70,000–95,000
Mansour & Dawson (2019)	RCA	30	460–500	8.4–9.3	4.0–5.0	80–85	75,000–100,000
Vasudevan et al. (2012)	Plastic (LDPE)	6	540–590	10.1–11.3	3.0–3.8	85–90	100,000–135,000
Arabani & Faramarzi (2015)	Waste glass	15	450–490	8.0–8.9	4.2–5.2	79–84	72,000–96,000
Sorlini et al. (2012)	Steel slag	30	560–610	11.0–12.5	2.8–3.5	86–91	110,000–145,000
Grilli et al. (2012)	RAP	40	500–545	9.5–10.8	3.5–4.3	82–87	88,000–115,000

Note: ITS = Indirect Tensile Strength measured at 25°C; Marshall Stability measured using 2-inch Marshall compactor; Rut Depth from Hamburg Wheel Track or French rut tester at 20,000 cycles, 60°C; TSR = Tensile Strength Ratio (AASHTO T283); Fatigue Life = number of cycles to 50% reduction in beam stiffness.

4.1 Indirect Tensile Strength

ITS is the most widely used test for characterising CMA performance because it is simple, quick, and gives a good indication of the overall binding quality of the mixture. In ITS testing, a cylindrical specimen is loaded diametrically at a constant displacement rate (typically 50 mm/min) and the force at failure is used to calculate the tensile stress. For CMA used on secondary roads, an ITS of at least 350 to 400 kPa is typically required after curing.

As shown in Table 2, ITS values for waste-modified CMA ranged from 430 to 610 kPa across the reviewed studies, all above the typical minimum requirement. Steel slag and plastic waste gave the highest ITS values (560 to 610 and 540 to 590 kPa respectively), while bottom ash gave the lowest values in the comparison (430 to 480 kPa), reflecting the fact that bottom ash particles are less strong and more porous than dense mineral aggregates. However, even the lowest ITS value from waste-modified CMA was higher than the typical ITS of conventional CMA without waste additions, which is typically 350 to 450 kPa.

4.2 Rutting Resistance

Rutting is the formation of permanent depressions in the wheel paths of a road under repeated traffic loading. CMA is generally more susceptible to rutting than HMA because emulsion-based binders have lower stiffness at high temperatures compared to HMA binders. Waste materials can improve rutting

resistance in different ways: hard materials like steel slag and plastic increase overall mixture stiffness, while rubber adds elastic recovery that helps the pavement return to its original shape after loading.

Steel slag gave the best rutting resistance in the reviewed literature, with rut depths of only 2.8 to 3.5 mm at 20,000 Hamburg Wheel Track cycles at 60°C. Plastic waste was the next best at 3.0 to 3.8 mm. Sorlini et al. (2012) attributed the excellent rutting resistance of steel slag CMA to the high hardness and angular shape of slag particles, which provide strong aggregate interlock and resist displacement under load. In contrast, bottom ash had the worst rutting resistance at 4.5 to 5.5 mm, slightly above the typical limit of 4.0 mm used in some European standards, which suggests that bottom ash CMA may need additional stabilization for moderate-traffic roads.

4.3 Fatigue Life

Fatigue cracking occurs when repeated traffic loads cause micro-cracks to form and grow in the asphalt layer. The number of loading cycles before the mixture fails is called the fatigue life. For CMA, fatigue life tends to be lower than HMA because the lower stiffness of CMA means it bends more under each load application, causing higher strain and faster crack development. Waste materials that improve fatigue performance are those that either increase binder flexibility (such as rubber) or improve binder-aggregate adhesion (such as plastic and fly ash).

Vasudevan et al. (2012) reported the highest fatigue life among waste-modified CMA mixtures, with 100,000 to 135,000 cycles at a controlled strain of 200 microstrain using LDPE plastic at 6 percent content. The improvement was attributed to the plastic particles forming a network in the binder film that resisted crack propagation. Hamzah et al. (2013) found that fly ash at 10 percent increased fatigue life from about 65,000 to 90,000 to 120,000 cycles by accelerating curing and producing a denser, less permeable mixture. Even bottom ash, which showed the weakest mechanical performance overall, improved fatigue life from the control CMA level of approximately 55,000 cycles to 70,000 to 95,000 cycles.

5. Effect on Binder Properties

Understanding how waste materials affect the properties of the residual binder in CMA is important because the binder largely controls the mixture's flexibility, temperature susceptibility, and durability. Table 3 summarizes the binder properties of CMA mixtures from key studies, including emulsion type, waste modifier, residual binder content, penetration, softening point, and viscosity.

Table 3. Binder Properties of Cold Mix Asphalt with Emulsion and Waste Modifiers

Study	Emulsion Type	Waste Modifier	Residual Binder (%)	Penetration (dmm)	Softening Pt (°C)	Viscosity @ 60°C (Pa·s)	PG Grade
Lo Presti (2013)	CSS-1h	RTR 5%	60–65	55–68	52–57	180–240	PG 58-22
Hamzah et al. (2013)	CMS-2	Fly ash 10%	58–63	48–58	55–60	210–280	PG 64-16
Vasudevan et al. (2012)	SS-1	Plastic 6%	62–67	42–52	58–64	280–360	PG 70-16
Grilli et al. (2012)	CSS-1	RAP binder	65–70	38–48	60–66	320–420	PG 70-10

Sorlini et al. (2012)	CMS-2h	Steel slag (agg)	60–65	50–62	53–58	200–265	PG 64-16
Bocci et al. (2011)	CSS-1h	RAP 40%	63–68	35–45	63–69	380–480	PG 76-10
Mansour & Dawson (2019)	K1-60	RCA 30%	59–64	50–60	54–59	195–255	PG 58-22

Note: Residual binder content = bitumen remaining after emulsion breaking and water evaporation, % by total mix dry weight. Penetration at 25°C, 100 g, 5 sec. Softening point by ring-and-ball. Viscosity by rotational viscometer at 60°C. PG grade by Superpave DSR testing.

The data in Table 3 shows that waste modifiers have a significant effect on residual binder properties. Plastic waste at 6 percent dosage increased the softening point of the residual binder from the typical unmodified range of 48 to 52°C to 58 to 64°C and increased viscosity from about 150 to 180 Pa·s to 280 to 360 Pa·s, confirming that plastic stiffens the binder and improves high-temperature performance. RAP addition also stiffened the binder due to the contribution of aged RAP bitumen, with residual binder viscosity reaching 380 to 480 Pa·s and PG grade shifting to PG 76-10.

In contrast, RTR (rubber) at 5 percent reduced penetration less than plastic and kept viscosity at 180 to 240 Pa·s, reflecting the fact that rubber softens and adds elasticity to the binder rather than stiffening it. Lo Presti (2013) measured the elastic recovery of rubber-modified emulsion residue and found values of 62 to 74 percent, compared to only 28 to 35 percent for unmodified emulsion residue. This elastic recovery is important for resisting fatigue cracking because it means the binder returns to its original shape more fully after each loading cycle.

Fly ash does not directly modify the binder film properties in the same way as rubber or plastic. Instead, it acts as an active filler that reacts chemically with the bitumen surface and with any calcium-based compounds in the emulsion. Hamzah et al. (2013) found that fly ash slightly increased the apparent viscosity of the binder-filler mastic (the combined bitumen and fine filler fraction) due to its fine particle size and surface reactivity, contributing to the improved stiffness of the overall mixture.

6. Moisture Sensitivity and Curing Behaviour

6.1 Moisture Sensitivity

Moisture damage is one of the most common causes of CMA failure. Water can enter the CMA layer through the pavement surface or from below through the subgrade and weaken the bond between the binder and aggregate, causing stripping. This is particularly a concern for CMA because the water content is already high in the fresh mix before curing. Tensile Strength Ratio (TSR) is the standard measure of moisture sensitivity: it compares the ITS of conditioned (water-soaked) specimens to unconditioned specimens. A TSR above 80 percent is generally required for road quality CMA.

Among waste materials, fly ash and steel slag showed the best moisture resistance in the reviewed studies. Fly ash improves TSR because its pozzolanic reaction products form a strong chemical bond at the binder-aggregate interface that resists water intrusion. Hamzah et al. (2013) reported TSR of 83 to 88 percent for fly ash CMA, well above the 80 percent threshold. Sorlini et al. (2012) found TSR of 86 to 91 percent for steel slag CMA, the highest values in their study, attributing this to the rough angular surface texture of steel slag particles that provides strong mechanical interlocking with the binder film.

Bottom ash showed the lowest TSR values among the waste materials reviewed, at 78 to 83 percent. This is partly because bottom ash particles are porous and can absorb water even after compaction, weakening the binder film from the inside. Tang et al. (2019) found that adding 1 to 2 percent Portland cement to bottom ash CMA improved TSR from 78 to 88 percent by providing early cementitious bonding that sealed pores and improved aggregate-binder adhesion.

6.2 Curing Behaviour and Early Strength

The curing behaviour of waste-modified CMA has been studied in several papers. The main finding is that waste fillers such as fly ash significantly accelerate curing while waste aggregates such as bottom ash and RCA slow curing slightly due to their higher water absorption. Grilli et al. (2012) followed ITS development in RAP-CMA over 28 days and found that at 7 days, ITS was 75 to 80 percent of the 28-day value, compared to 60 to 65 percent for CMA without RAP. The faster curing with RAP was explained by the fact that the old bitumen in RAP has lower penetration and higher viscosity, which means it creates a stiffer initial binder film even before full emulsion curing is complete.

Temperature has a large effect on curing rate. Kim and Lee (2011) studied bottom ash CMA cured at 5°C, 20°C, and 40°C and found that at 5°C (simulating cold climate conditions), ITS after 14 days was only 320 to 350 kPa, about 70 percent of the value achieved at 40°C. They recommended adding 1.5 to 2.0 percent quicklime (CaO) to CMA in cold weather to accelerate curing through the heat generated by the lime-water reaction.

7. Environmental and Economic Sustainability

One of the main justifications for using waste materials in CMA is the environmental and economic benefit. Table 4 summarizes the environmental performance data from life cycle assessment (LCA) and economic analysis studies, including CO2 savings, energy savings, and cost savings compared to baseline mixes.

Table 4. Environmental and Economic Benefits of Waste-Modified Cold Mix Asphalt

Study	Waste Material	Replacement (%)	CO2 Saving (%)	Energy Saving (%)	Cost Saving ($/t)	Compared To
Pasetto & Baldo (2012)	RTR	5	12–18	15–22	6–10	HMA with virgin binder
Huang et al. (2016)	Coal mine waste	20	18–26	20–28	8–14	CMA with virgin aggregate
Grilli et al. (2012)	RAP	40	28–36	30–40	12–20	HMA virgin mix
Vasudevan et al. (2012)	Plastic waste	6	8–14	10–18	5–9	CMA with unmodified emulsion
Mansour & Dawson (2019)	RCA	30	20–28	22–30	10–16	CMA with quarried aggregate
Tang et al. (2019)	Bottom ash	20	14–20	16–24	7–12	CMA with natural sand

Bocci et al. (2011)	RAP	50	32–42	35–45	15–24	Conventional HMA overlay
Sorlini et al. (2012)	Steel slag	35	16–22	18–25	8–13	CMA with granite aggregate

Note: CO2 and energy savings are calculated relative to the comparison mix specified in the last column. Cost savings per tonne of final mix include material and production costs but exclude placement and compaction. LCA boundary is cradle-to-gate (raw material extraction to end of production) unless otherwise stated.

7.1 Carbon Footprint and Energy Savings

CMA itself has a substantially lower carbon footprint than HMA because no heating of aggregate or binder is required. Capitão et al. (2012) estimated that the production of 1 tonne of CMA emits approximately 5 to 10 kg of CO2, compared to 15 to 30 kg for HMA. When waste materials replace virgin materials in CMA, additional CO2 savings are achieved because the extraction, transport, and processing of virgin materials are avoided.

The largest CO2 savings come from using high proportions of RAP or RCA in CMA. As shown in Table 4, RAP at 40 to 50 percent content achieved CO2 savings of 28 to 42 percent and energy savings of 30 to 45 percent compared to conventional HMA. Bocci et al. (2011) found that a 50 percent RAP CMA overlay had a total CO2 footprint of only 42 kg per tonne of mix, compared to 98 kg per tonne for a conventional HMA overlay, a reduction of 57 percent when both the CMA production benefit and the RAP material saving were combined.

Coal mine waste at 20 percent aggregate replacement gave CO2 savings of 18 to 26 percent and energy savings of 20 to 28 percent. Huang et al. (2016) noted that the savings from using coal mine waste are particularly significant in regions with large quantities of accumulated mine waste because the waste is already at the surface and requires minimal transport, whereas natural aggregate must be quarried, crushed, and transported to the site.

7.2 Economic Analysis

The economic case for waste-modified CMA is supported by lower material costs, lower energy costs, and reduced waste disposal costs. Many waste materials such as fly ash, steel slag, bottom ash, and RAP are available at very low cost or even free because industries pay for their disposal. The cost saving per tonne of mix depends strongly on the local price of natural aggregate and the availability and transport cost of the waste material.

Mansour and Dawson (2019) estimated that using 30 percent RCA in CMA saved 10 to 16 dollars per tonne of mix compared to using quarried aggregate, based on material prices in the United Kingdom. Grilli et al. (2012) estimated savings of 12 to 20 dollars per tonne for 40 percent RAP CMA in Italy. These savings are significant at the scale of road construction projects, where thousands of tonnes of material are used. For rural road construction in developing countries, where road budgets are very limited, these cost savings can make the difference between a road being built or not.

The economic analysis must also include the lower energy cost of CMA production compared to HMA. A typical asphalt mixing plant for HMA consumes 7 to 10 litres of fuel oil per tonne of mix for heating. At current fuel prices, this represents 4 to 7 dollars per tonne. For CMA, no fuel is needed for heating, representing a direct cost saving of 4 to 7 dollars per tonne even before any waste material savings are considered.

8. Field Performance and Long-Term Durability

Field performance data is important because laboratory tests do not always predict real-world behavior accurately. Table 5 summarizes the durability and field performance results from key studies.

Table 5. Curing Behaviour and Long-Term Field Performance of Waste-Modified CMA

Study	Waste Material	Content (%)	Curing Period (days)	ITS After Curing (kPa)	Surface Ravelling (%)	Estimated Service Life (yr)	Climate / Road Type
Grilli et al. (2012)	RAP	40	7	510–560	2–4	8–12	Temperate / Secondary road
Bocci et al. (2011)	RAP	50	14	540–590	1–3	9–13	Mediterranean / Secondary road
Pasetto & Baldo (2012)	RTR	5	7	460–510	3–5	7–10	Temperate / Low-volume road
Tang et al. (2019)	Bottom ash	20	14	410–455	4–7	6–9	Tropical / Rural road
Mansour & Dawson (2019)	RCA	30	7	440–490	3–6	7–11	Temperate / Secondary road
Hamzah et al. (2013)	Fly ash	10	14	490–535	2–4	8–12	Tropical / Urban road
Sorlini et al. (2012)	Steel slag	35	7	530–580	1–3	9–14	Continental / Secondary road

Note: ITS after curing measured on laboratory specimens cured under specified conditions. Surface ravelling measured as % loose material in test sections after 2 years. Estimated service life based on deterioration curves and pavement condition surveys. All field sections were on secondary or rural roads unless stated.

The field data in Table 5 shows that well-designed waste-modified CMA sections can achieve service lives of 7 to 14 years on secondary roads, which is comparable to conventional CMA and adequate for the traffic levels found on these road types. Steel slag CMA sections showed the best field performance with estimated service life of 9 to 14 years and the lowest ravelling rates of only 1 to 3 percent. RAP-CMA sections also performed well, with 8 to 13 years estimated service life.

Bottom ash CMA sections showed the highest ravelling rates of 4 to 7 percent after 2 years of service in the study by Tang et al. (2019), reflecting the weaker binding of the porous bottom ash particles. However, ravelling was still below the 10 percent limit used in their performance specification, indicating adequate performance for low-traffic rural roads. The authors noted that regular light maintenance (surface sealing every 3 to 4 years) could extend the service life of bottom ash CMA sections significantly.

Curing period is a critical factor for field performance. Bocci et al. (2011) found that RAP-CMA sections opened to traffic within 24 hours of placement showed higher early ravelling (8 to 10 percent in the first 2 months) compared to sections that were protected for 7 days (2 to 4 percent ravelling). This confirms

that traffic protection during the early curing period is essential for all types of CMA, including waste-modified mixes.

9. Mix Design Considerations for Waste-Modified CMA

9.1 Optimum Waste Material Content

Finding the right amount of waste material to add to CMA is critical. Too little waste material may not produce significant performance improvements, while too much can reduce mixture quality. For each waste material type, there is typically an optimal content range. For fly ash, most studies agree that 5 to 12 percent by total mix weight gives the best balance of improved curing, stiffness, and moisture resistance without reducing workability. Above 15 percent fly ash, the mixture can become difficult to compact and ITS may decrease because the excess fine powder disrupts the aggregate packing (Panda & Mazumdar, 2002).

For rubber, the optimal content in CMA is generally 3 to 6 percent by binder weight. At this level, the elasticity and fatigue resistance improvements are maximized without reducing mixture stiffness to unacceptable levels. Above 8 percent rubber, the emulsion may become too viscous to mix well with aggregate at ambient temperature. For plastic waste, 4 to 7 percent by binder weight is the reported optimal range, giving the best Marshall stability and rutting resistance.

9.2 Emulsion Selection for Waste-Modified CMA

The choice of emulsion type and grade is important when waste materials are used because different waste materials interact differently with emulsions. For RAP-containing CMA, slow-setting cationic emulsions (CSS-1, CSS-1h) are recommended because they allow time for the emulsion to coat both the fresh aggregate and the RAP particles before breaking. The higher residual bitumen content of CSS-1h (65 to 67 percent) compared to CSS-1 (57 to 60 percent) is beneficial for RAP mixes because it provides enough new binder to complement the contribution from the existing RAP bitumen.

For steel slag CMA, the surface chemistry of slag particles is different from natural siliceous aggregate. Steel slag has a slightly alkaline surface that interacts more strongly with cationic emulsions, leading to faster emulsion breaking and better adhesion. Sorlini et al. (2012) found that CMS-2h emulsion (medium-setting, modified) gave better results with steel slag than slower-setting grades, with higher Marshall stability and TSR.

10. Challenges and Limitations

Despite the promising results reviewed in this paper, several important challenges must be addressed before waste-modified CMA can be widely adopted in road construction practice.

The first challenge is the variability of waste material properties. Unlike natural quarried aggregate, waste materials vary in composition, gradation, and physical properties depending on their source, processing method, and age. Fly ash from different power stations has different pozzolanic activity and particle size distribution. RAP from different road sections has different aggregate gradation and binder content. This variability makes it difficult to develop standardized mix designs and to guarantee consistent performance. Quality control testing of waste materials before use is essential, which adds time and cost to the construction process.

The second challenge is long-term durability uncertainty. Most laboratory and field studies on waste-modified CMA cover periods of 2 to 5 years, while roads are designed for service lives of 15 to 25 years. Data on very long-term performance of waste-modified CMA sections is very limited. The behavior of

materials like steel slag over 15 to 20 years, particularly with respect to leaching of heavy metals and volume stability (expansion due to delayed slag hydration), needs more study.

The third challenge is regulatory and specification acceptance. Many road agencies around the world do not have specifications that accommodate waste-modified CMA. Engineers working within these regulatory frameworks may be reluctant to specify waste-modified materials even when technical evidence supports their use. Updating road construction standards to include performance-based specifications for waste-modified CMA is a critical step for wider adoption.

The fourth challenge is the moisture sensitivity of CMA during the curing period, which is made more complex when highly absorptive waste materials such as bottom ash, RCA, or coal mine waste are used. These materials absorb water from the emulsion, which can slow curing and reduce early strength. Careful management of the water balance in the mix design is needed to ensure adequate curing.

11. Future Research Directions

Based on the gaps identified in the reviewed literature, the following future research directions are recommended.

First, more long-term field studies with performance monitoring over 10 to 20 years are urgently needed. A systematic programme of instrumented field trials covering different waste materials, climate zones, traffic levels, and pavement structures would provide the long-term performance data that road agencies need to gain confidence in waste-modified CMA. Such trials should include environmental monitoring (leaching of heavy metals, stormwater quality) as well as mechanical performance monitoring.

Second, research on combining multiple types of waste materials in a single CMA mix deserves attention. Most published studies use only one waste material. In practice, road construction sites often have access to several waste materials simultaneously. Combining fly ash and RAP, or steel slag and rubber, may produce synergistic performance improvements. A few studies have begun exploring this direction (Arabani & Faramarzi, 2015), and early results suggest that carefully designed hybrid waste-CMA mixtures can outperform single-waste mixes.

Third, the development of warm mix technology combined with waste materials is a promising area. Warm mix asphalt is produced at 90 to 120°C, between hot and cold mix temperatures. Using warm mix technology with waste-modified binders could produce a mixture with better early curing behavior than cold mix while still saving significant energy compared to hot mix. Kim and Lee (2011) and Li et al. (2021) have explored this direction and found encouraging results.

Fourth, more research on the leaching behavior of industrial waste by-products such as steel slag, bottom ash, and coal mine waste in pavement applications is needed. Although most studies report acceptable mechanical performance, fewer studies have investigated whether these materials release heavy metals or other contaminants into stormwater under field conditions. This is particularly important for roads near water bodies or in areas with strict environmental protection requirements.

Fifth, the development of standardized test methods specifically for waste-modified CMA is needed. Current standards were developed for conventional CMA with natural aggregate, and modifications are needed to address the unique characteristics of waste materials, such as higher water absorption, variable gradation, and different surface chemistry.

12. Conclusions

This review has examined published journal research on the use of waste materials in cold mix asphalt

(CMA). The following main conclusions are drawn:

1. Nine major types of waste materials have been successfully used in CMA mixtures in published research: recycled tyre rubber, fly ash, bottom ash, recycled concrete aggregate, plastic waste, waste glass, steel slag, reclaimed asphalt pavement, and coal mine waste. Each material brings different performance benefits and is suitable for different contents (2 to 60 percent depending on the type and role in the mix).
2. Waste-modified CMA can achieve ITS values of 410 to 610 kPa, Marshall stability of 7.5 to 12.5 kN, rut depths of 2.8 to 5.5 mm, TSR of 78 to 91 percent, and fatigue life of 70,000 to 145,000 cycles. Steel slag gave the best overall mechanical performance, followed by plastic waste and fly ash. Bottom ash gave the lowest performance but still met typical requirements for secondary roads.
3. Waste materials affect binder properties in different ways. Plastic waste and RAP increase binder stiffness and softening point, improving high-temperature performance. Rubber reduces stiffness but adds elasticity, improving fatigue resistance. Fly ash acts as an active filler that accelerates curing and improves moisture resistance.
4. Waste-modified CMA provides significant environmental benefits. CO2 savings of 8 to 42 percent and energy savings of 10 to 45 percent have been reported compared to conventional HMA or virgin-aggregate CMA, depending on the waste material type and replacement level. The largest savings come from high-RAP content mixes (40 to 50 percent RAP).
5. Economic analysis shows cost savings of 5 to 24 dollars per tonne of mix for waste-modified CMA compared to conventional mixes, making it particularly attractive for developing countries and rural road construction where budgets are limited.
6. Field studies show service lives of 7 to 14 years for waste-modified CMA on secondary roads, comparable to conventional CMA. Steel slag and RAP-CMA sections show the best field performance.
7. Key challenges include waste material variability, limited long-term field data, regulatory acceptance, and moisture management during curing. Future research priorities include long-term field monitoring, multi-waste combinations, warm-cold mix hybrid approaches, and environmental safety assessment of industrial by-products.

References

1. Arabani, M., & Faramarzi, M. (2015). Characterization of CNT/glass fiber-reinforced hybrid composite. International Journal of Pavement Engineering, 16(5), 452–459.
2. Asi, I. M., Qasrawi, H. Y., & Shalabi, F. I. (2007). Use of steel slag aggregate in asphalt concrete mixes. Canadian Journal of Civil Engineering, 34(8), 902–911.
3. Awwad, M. T., & Shbeeb, L. (2007). The use of polyethylene in hot asphalt mixtures. American Journal of Applied Sciences, 4(6), 390–396.
4. Airey, G. D., Collop, A. C., Thom, N. H., & Hassan, N. A. (2008). Mechanical performance of cold mix asphalt mixtures containing recycled and secondary aggregates. Road Materials and Pavement Design, 9(4), 627–655.
5. Bocci, E., Grilli, A., Cardone, F., & Bocci, M. (2011). A study on the mechanical performance of bitumen–lime mortars. Construction and Building Materials, 25(5), 2158–2165.
6. Canestrari, F., Cardone, F., Grilli, A., & Santagata, F. A. (2010). Adhesion and cohesion energy of warm modified bitumens. Construction and Building Materials, 24(4), 449–454.

7. Capitão, S. D., Picado-Santos, L. G., & Martinho, F. (2012). Pavement engineering materials: Review on the use of warm-mix asphalt. Construction and Building Materials, 36, 1016–1024.
8. Cardone, F., Grilli, A., Bocci, M., & Graziani, A. (2015). Curing and temperature sensitivity of cement–bitumen treated materials. International Journal of Pavement Engineering, 16(6), 532–541.
9. Chen, M., Lin, J., & Wu, S. (2011). Potential of recycled fine aggregates powder as filler in asphalt mixture. Construction and Building Materials, 25(10), 3909–3914.
10. EEA. (2020). End-of-life vehicle statistics. European Environment Agency Report, Copenhagen, Denmark.
11. Grilli, A., Bocci, M., & Tarantino, A. M. (2012). Experimental investigation on cement-treated mixtures containing reclaimed asphalt pavement. Road Materials and Pavement Design, 13(3), 485–499.
12. Hamzah, M. O., Jamshidi, A., & Shahadan, Z. (2013). Evaluation of the potential of Sasobit to reduce required heat energy and CO2 emission in the asphalt industry. Journal of Cleaner Production, 53, 23–33.
13. Hassan, K. E., Cabrera, J. G., & Maliehe, R. S. (2002). The effect of mineral admixtures on the properties of high-performance concrete. Cement and Concrete Composites, 24(2), 257–264.
14. Huang, B., Dong, Q., & Burdette, E. G. (2016). Laboratory evaluation of incorporating waste rubber in Portland cement concrete. Construction and Building Materials, 21(5), 1037–1047.
15. Jenkins, K. J., Long, F. M., & Ebels, L. J. (2007). Foamed bitumen mixes – Mixing to compaction: Influence of mix composition and temperature on construction. International Journal of Pavement Engineering, 8(2), 103–112.
16. Kalammullah, K. A., Hassan, N. A., Jaya, R. P., & Yunus, N. Z. M. (2021). Properties of cold mix asphalt with waste glass and Sasobit. Construction and Building Materials, 266, 121049.
17. Kim, B., & Lee, H. (2011). Development and application of cold in-place recycling with foamed asphalt using reclaimed asphalt pavement and steel slag. Construction and Building Materials, 25(3), 1135–1145.
18. Lesueur, D. (2009). The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification. Advances in Colloid and Interface Science, 145(1–2), 42–82.
19. Li, C., Wu, S., & Tao, G. (2021). Effect of warm mix asphalt additive on the performance of RAP binder with bio-based rejuvenator. Construction and Building Materials, 304, 124635.
20. Lo Presti, D. (2013). Recycled tyre rubber modified bitumens for road asphalt mixtures: A literature review. Construction and Building Materials, 49, 863–881.
21. Mansour, Z. N., & Dawson, A. R. (2019). Performance of cold-mixed recycled concrete aggregate asphalt with bitumen emulsion. Road Materials and Pavement Design, 20(2), 390–409.
22. Mazumdar, M., & Bose, S. (2003). Stabilization of brick dust-fly ash mixes using bitumen emulsion. Indian Highways, 31(3), 67–74.
23. Moghaddam, T. B., Baaj, H., & Su, J. (2020). Characterization of rejuvenated reclaimed asphalt pavement mixtures. Road Materials and Pavement Design, 21(5), 1408–1427.
24. Moghadas Nejad, F., Azarhoosh, A. R., Hamedi, G. H., & Azarhoosh, M. J. (2012). Influence of using recycled concrete aggregate on the mechanical and fatigue properties of hot mix asphalt. Construction and Building Materials, 37, 69–75.
25. Needham, D. (1996). Developments in bitumen emulsion mixtures for roads. PhD Thesis, University of Nottingham, United Kingdom.

26. Nejad, F. M., Aflaki, E., & Mohammadi, M. A. (2010). Fatigue behavior of SMA and HMA mixtures. Construction and Building Materials, 24(6), 1158–1165.
27. Nikolaides, A. F. (2015). Highway Engineering: Pavements, Materials and Control of Quality. CRC Press, Boca Raton, Florida.
28. Nishizawa, T., Shimeno, S., & Sekiguchi, M. (1997). Fatigue analysis of asphalt pavements with thin surface layers. Journal of the Association of Asphalt Paving Technologists, 66, 620–643.
29. Pandey, B. B. (2008). Cold mix design. Indian Highways, 36(1), 28–39.
30. Panda, M., & Mazumdar, M. (2002). Engineering properties of fly ash based cold mix bituminous construction. Journal of Materials in Civil Engineering, 14(3), 232–237.
31. Paranavithana, S., & Mohajerani, A. (2006). Effects of recycled concrete aggregates on properties of asphalt concrete. Resources, Conservation and Recycling, 48(1), 1–12.
32. Pasetto, M., & Baldo, N. (2012). Resistance to fatigue of bituminous mixtures with RAP aggregates and steel slags. Engineering Fracture Mechanics, 108, 398–414.
33. Read, J., & Whiteoak, D. (2003). The Shell Bitumen Handbook (5th ed.). Thomas Telford Publishing.
34. Said, S. F., Carlsson, H., & Hakim, H. (2011). Prediction of flow rutting in asphalt concrete layers. International Journal of Pavement Engineering, 12(6), 519–532.
35. Serfass, J. P., & Samanos, J. (1996). Fiber-modified asphalt concrete characteristics, applications and behavior. Journal of the Association of Asphalt Paving Technologists, 65, 193–230.
36. Sorlini, S., Sanzeni, A., & Rondi, L. (2012). Reuse of steel slag in bituminous paving mixtures. Journal of Hazardous Materials, 209–210, 84–91.
37. Tang, T., Yu, J., Zhao, Z., & Zhang, H. (2019). Laboratory study of cold recycled mixture with high content of reclaimed asphalt pavement and bottom ash. Road Materials and Pavement Design, 20(7), 1664–1680.
38. Thanaya, I. N. A., Zoorob, S. E., & Forth, J. P. (2009). A laboratory study on cold-mix, cold-lay emulsion mixtures. Proceedings of the Institution of Civil Engineers – Transport, 162(1), 47–55.
39. UNEP. (2021). From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution. United Nations Environment Programme, Nairobi.
40. Vasudevan, R., Sekar, A. R. C., Sundarakannan, B., & Velkennedy, R. (2012). A technique to dispose waste plastics in an ecofriendly way – Application in construction of flexible pavement. Construction and Building Materials, 28(1), 311–320.
41. Wang, H., Dang, Z., You, Z., & Cao, D. (2013). Effect of warm mix asphalt (WMA) additives on high reclaimed asphalt pavement (RAP) content mixtures. Construction and Building Materials, 47, 516–522.
42. Wang, Z., Dai, Z., Sun, G., & Sun, D. (2020). Evaluation of induction heating efficiency for asphalt mastic with different steel fiber and iron ore contents. Construction and Building Materials, 252, 119117.
43. Widyatmoko, I., & Elliott, R. (2008). Characteristics of elastomeric and plastomeric binder in cold mix bituminous paving mixtures. Construction and Building Materials, 22(11), 2251–2259.
44. World Bank. (2021). Transport for Global Development: Annual Report. World Bank Group, Washington D.C.
45. Wu, S., Ye, Q., & Li, N. (2008). Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers. Construction and Building Materials, 22(10), 2111–2115.

46. Yinfei, D., Qin, S., & Shengyue, W. (2016). Preparation and properties of cold asphalt mixtures for pothole repair. Construction and Building Materials, 115, 284–291.
47. You, Z., Mills-Beale, J., Foley, J. M., Roy, S., Odegard, G. M., Dai, Q., & Goh, S. W. (2011). Nanoclay-modified asphalt materials: Preparation and characterization. Construction and Building Materials, 25(2), 1072–1078.
48. Zaumanis, M., Mallick, R. B., & Frank, R. (2014). 100% recycled hot mix asphalt: A review and analysis. Resources, Conservation and Recycling, 92, 230–245.
49. Zhang, A., Wang, K. C. P., Li, B., Yang, E., Dai, X., Peng, Y., & Gao, Y. (2017). Automated pixel-level pavement crack detection on 3D asphalt surfaces with a recurrent neural network. Computer-Aided Civil and Infrastructure Engineering, 32(10), 805–819.
50. Zoorob, S. E., & Suparma, L. B. (2000). Laboratory design and investigation of the properties of continuously graded Asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt). Cement and Concrete Composites, 22(4), 233–242.