

Colouring penetration-grade bitumen through emulsification and optical masking with a light mineral phase: laboratory development and process design

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Research Article

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Abstract

Conventional bitumen is intensely black because of its asphaltene fraction, so pigments added to it yield only dark shades, whereas synthetic clear binders that accept any colour are costly. This study developed a route that lightens ordinary 80/100 penetration-grade bitumen before colouring. Six sequential laboratory attempts were made using a one-factor-at-a-time approach. Direct addition of an orange dye at 7.4% of bitumen mass changed the colour only from black to dark brown, and fillers or clay mixed into hot bitumen produced no visible lightening. A bitumen-in-water emulsion was stabilised by controlling water content, agitation and emulsifier type. When calcium hydroxide filler and montmorillonite clay were added after emulsification, rather than to the hot bitumen, the binder turned from black to grey, and the grey base could be tinted with less colourant. A polymer-modified binder restored binding capacity, but textile dyes gave poor colour fastness. The procedure was scaled into a continuous process with material and energy balances for 265 kg h⁻¹ of coloured emulsion (157 kg h⁻¹ dry binder). The process requires about 0.22 MJ of heat and 0.077 kWh of electricity per kilogram of dry binder, and its raw-material cost was about 1.4 times the price of plain bitumen at the prices of the study. The results indicate that optical masking of emulsified bitumen is a low-cost route to coloured binders; instrumental colour, durability and mixture performance testing are needed before field use.

1 Introduction

Bitumen is the heavy residue of crude-oil refining and the dominant binder of flexible pavements. It is commonly described as a colloidal system in which high-molecular-weight asphaltenes are dispersed in a continuous phase of lower-molecular-weight maltenes [1]. The asphaltenes absorb strongly across the visible spectrum, which gives bitumen its black colour and makes conventional pavements highly absorptive of solar radiation.

Coloured pavements are used to demarcate bus lanes, cycle tracks, pedestrian crossings and hazard zones, to improve the appearance of public spaces and sports surfaces, and, because lighter surfaces reflect more solar energy, to reduce surface temperature and mitigate the urban heat island (UHI) [2, 3]. Three routes are in use. Pigments, usually iron oxides, can be added to conventional mixtures, but against a black binder only dark red, brown or green shades are obtainable [4, 5]. Synthetic clear binders accept any pigment but cost several times as much as bitumen [6, 7]. Thin coloured surface treatments give strong colours but wear under traffic [8].

A route is therefore needed that produces a light, colourable binder from ordinary penetration-grade bitumen without the cost of clear binders and without the high colourant loadings required in black bitumen. The hypothesis of this work is that, once bitumen is dispersed as fine droplets in an aqueous emulsion, the droplets can be optically concealed by a fine, light-coloured mineral phase, producing a grey base that can then be tinted economically. The objectives were to (i) establish the failure of direct colouring as a baseline, (ii) identify conditions for a stable emulsion, (iii) develop an emulsification-and-masking procedure giving a grey base, (iv) address binding capacity and colour fastness, and (v)

translate the procedure into a continuous process with material and energy balances and a raw-material cost estimate.

2 Background

2.1 Colour of bitumen and pigmented mixtures

An object appears coloured because it selectively absorbs part of the incident visible spectrum and reflects the remainder [9]. Bitumen absorbs nearly all visible wavelengths, so a colourant dispersed in it has very little reflected light to modify. Iron oxide pigments (red haematite, yellow goethite) and chromium(III) oxide are the standard colourants for asphalt and concrete because of their low cost, light fastness and chemical inertness [10]. Porto et al. [4] added 5 wt% red and yellow iron oxide to mixtures with a 50/70 binder; stiffness, rutting and fatigue resistance increased and the red mixture was up to 2.7°C cooler, but the yellow pigment performed poorly because a light colour cannot show against a dark binder. Badin et al. [11] reported surface-temperature reductions of up to 5°C with titanium dioxide and red iron oxide, and Khalifa et al. [5] produced red and green binders with iron and chrome oxides with satisfactory performance.

2.2 Synthetic clear binders and surface treatments

Clear binders are blends of petroleum resins, oils and polymers that mimic the rheology of bitumen without asphaltenes [1]. Pasetto et al. showed that a clear synthetic resin is suitable for wearing courses, although less stiff than bitumen [6], and that clear and coloured mixtures run cooler [12]. Tang et al. [13] examined the rheology of light-coloured synthetic binders with polymer modifiers. Badin et al. [7] found clear-binder mixtures up to 9°C cooler than black asphalt and up to 11°C cooler when pigmented, and Osman et al. [14] reported that pigmented clear-binder mixtures had lower Marshall stability but better moisture resistance and flexibility than conventional asphalt concrete. Their main drawback remains cost. Coloured surface treatments and coatings are an alternative: Kinouchi et al. [15] developed a dark, near-infrared-reflective coating that lowered surface temperature by about 15°C, Autelitano and Giuliani [16] studied the day and night appearance of pigmented treatments, and Wang et al. [8] showed that the durability of coloured ultra-thin overlays depends on binder depth and chip spreading rate.

2.3 Bitumen emulsions and particle-stabilised interfaces

A bitumen emulsion is a dispersion of bitumen droplets, typically 1–10 µm, in water, produced by feeding hot bitumen and a hot emulsifier solution to a colloid mill [17, 18]. Stability depends on bitumen content, emulsifier type and dose, temperature and shear. Colloidal clays have long been used as bitumen emulsifiers [17, 19], and fine solid particles are known to adsorb at oil–water interfaces and stabilise Pickering emulsions [20]. Once bitumen is present as discrete droplets, the droplet surfaces and the continuous aqueous phase become accessible to fine mineral particles. To the authors' knowledge, the use of this effect to conceal the black colour of bitumen before tinting has not been reported; this is the gap addressed here.

3 Materials and methods

3.1 Materials

The materials are listed in Table 1. The experimental work was carried out in 2010; Attempt 1 was performed at an industrial oil facility and Attempts 2–6 in the laboratory of the Department of Applied Chemistry and Chemical Technology at the authors' institution

Table 1
Materials used in the experimental programme

Material	Specification	Function
Bitumen	Penetration grade 80/100	Base binder
Gravel chips	Crushed aggregate	Substrate for coated samples
Filler	Calcium hydroxide; alumina, silica, kaolin (passing 100–200 mesh)	Light mineral phase
Masking agent	Montmorillonite clay, $\approx$ 200 mesh	Optical masking of droplets
Emulsifier	Methyl cellulose; colloidal silica	Emulsion stabilisation
Colourant	Orange reactive dye and dye blends	Tinting
Polymeric binder	Polymer-modified asphalt; natural or synthetic rubber latex	Restoring binding capacity
Fixing agents	Polyelectrolyte colour binder; sodium chloride	Colour fastness

3.2 Experimental procedure

An iterative approach was adopted: each attempt was designed in response to the outcome of the previous one. Within each attempt a one-factor-at-a-time study varied one of order of addition, time, temperature, agitation, water (slurry) content or emulsifier type while the others were held constant. Experiments were performed in open beakers at atmospheric pressure. Bitumen was heated on a hot plate to 100–110°C and mixed with a mechanical agitator; emulsifier slurries were prepared in boiling water because the emulsifier formed lumps in cold water. Each experiment lasted 1.5–2 h.

Attempt 1 added the dye directly to hot bitumen (200 g bitumen, 174 g gravel chips, 14.85 g dye). Attempt 2 mixed 15 g filler into 200 g hot bitumen for 30 min, followed by 10 g clay. Attempt 3 emulsified hot bitumen with water and emulsifier. Attempt 4 combined Attempts 2 and 3, adding the filler and clay either to the hot bitumen or after the emulsion had formed. Attempt 5 added colourant to the grey base, and Attempt 6 added a polymeric binder and fixing agents.

3.3 Evaluation

Colour was judged visually against untreated bitumen coated on gravel chips under daylight. Retention of binding capacity was checked qualitatively by the adhesion and cohesion of the coated chips, and colour and wash fastness by immersing coated samples in water. Instrumental colorimetry and standard mechanical tests were not available when the work was carried out; this limitation is discussed in Section 6.

3.4 Process design basis

The most successful laboratory procedure was scaled to a continuous process on a basis of one hour of steady operation. Material balances assumed steady state, no accumulation, no reaction and no evaporation within the process [21]. Sensible heat was calculated as $Q = m \cdot C_p \cdot \Delta T$ with $C_p = 0.92 \text{ kJ kg}^{-1} \text{ K}^{-1}$ for bitumen and bitumen–filler dispersion and $4.182 \text{ kJ kg}^{-1} \text{ K}^{-1}$ for water and aqueous slurry; latent heat was neglected because bitumen softens progressively [1]. Raw-material costs used the prices obtained at the time of the study, and the estimate followed the structure of standard design texts [22, 23].

4 Results and discussion

4.1 Direct colouring and addition of fillers to hot bitumen

In Attempt 1 the dye loading was 3.82 wt% of the coated sample and 7.4% of the bitumen mass, yet the colour changed only from black to dark brown. This agrees with the pigmented-mixture literature, in which only dark shades are obtained against a black binder [1, 4], and the route was judged uneconomic because of the high colourant consumption.

In Attempt 2 no lightening was obtained under any of the conditions tested (Table 2). When filler is mixed into continuous hot bitumen, each particle is wetted and enveloped by a black film, so the mixture remains black, which is the same reason asphalt mastic is black despite its high filler content.

4.2 Emulsification

In Attempt 3 a single phase formed transiently but broke on standing, indicating that either bitumen or water was in excess. The parametric trials (Table 2) identified water content, agitation intensity and emulsifier type as the governing variables, with temperature of secondary importance and time without effect. This is consistent with emulsion technology, in which the bitumen-to-water ratio and the shear applied govern droplet size and stability [17, 18]. The product was still black, but a stable emulsion was obtained, and the water quantity, mixer speed and emulsifier identified here form the basis of the process design.

Table 2
Summary of the parametric trials (one factor varied, others held constant)

Attempt	Variable	Effect observed
2 – filler and clay in hot bitumen	Order of addition, time, temperature, agitation	No reduction in black colour for any variable
3 – emulsification	Water content	Strong, decisive for stability
	Agitation; emulsifier type	Strong
	Temperature	Moderate
	Time	None
4 – emulsification + masking	Slurry : bitumen ratio	Moderate lightening before filler; high after filler
	Agitation	Slight before filler; moderate after filler
	Time; temperature	None

4.3 Emulsification combined with optical masking

Adding calcium hydroxide filler to the bitumen phase before emulsification again gave a jet-black product. However, when the filler and montmorillonite were added after a fluffy black emulsion had formed, the colour lightened markedly to grey. The slurry-to-bitumen ratio was the dominant variable (Table 2), and time and temperature had no measurable effect within the ranges tested.

The order-of-addition effect is the key result of the study. In continuous hot bitumen the mineral particles are coated by binder and become black; in an emulsion the bitumen is the dispersed phase, and fine, light particles occupy the aqueous continuous phase and the droplet surfaces, where they scatter incident light before it reaches the black droplets. This picture is consistent with the known ability of clays and other fine particles to adsorb at oil–water interfaces [19, 20]. A higher slurry-to-bitumen ratio increases the volume of light continuous phase per droplet, which explains its dominant influence.

4.4 Colouring the grey base, binding capacity and colour fastness

With the grey base, a visible colour was obtained with less colourant than in Attempt 1, and a wider range of shades was possible. Two problems appeared. First, emulsification and masking reduced the binding capacity of the bitumen; this was restored with a polymer-modified asphalt binder, consistent with the established role of polymers in improving cohesion and adhesion [24]. Second, colour and wash fastness were poor. A polyelectrolyte fixing agent improved fastness, but textile fixing agents were inadequate: reactive dyes are designed to bond covalently to hydroxyl groups in cellulose, and bitumen offers no such sites [9]. Light-fast inorganic pigments such as iron oxides, which are already proven in pigmented asphalt [4, 5], are therefore the logical colourant for the process.

Compared with the alternatives in Section 2, the proposed route starts from ordinary penetration-grade bitumen, avoiding the cost of clear binders [6, 7], while the grey base should widen the range of shades beyond the dark reds and browns attainable in black binders [4]. Because a lighter base also reflects more solar radiation, the route may share the thermal benefits reported for coloured and clear-binder pavements [11, 25], although this has not yet been measured.

5 Process design

5.1 Process description and material balance

The procedure of Attempts 4–6 was translated into a continuous process (Fig. 1). Bitumen is held at 100–120°C in an insulated, heated storage tank and transferred by a jacketed pump to mixer M-1, where filler is added to form a dispersion at 113–115°C. Water is heated to 80–90°C and fed to mixer M-2, where the emulsifier is added to form a slurry. The dispersion and slurry are fed to a colloid mill (rotor–stator, 4 kW), which produces a black emulsion. The masking agent is added in mixer M-3 to give a grey emulsion, and the colourant, polymeric binder and sodium chloride are added in mixer M-4. After application the water evaporates, leaving the coloured binder. The resulting product composition is given in Table 3.

Table 3
Product composition, wet and dry basis (basis: 1 h)

Component	Mass (kg)	Wet basis (wt%)	Dry basis (wt%)
Bitumen 80/100	91	34.34	57.96
Filler (calcium hydroxide)	9	3.40	5.73
Emulsifier	8	3.02	5.10
Masking agent (montmorillonite)	14	5.28	8.92
Sodium chloride	10	3.77	6.37
Polymeric binder	20	7.55	12.74
Colourant	5	1.89	3.18
Water	108	40.75	–
Total	265	100.00	100.00 (157 kg)

5.2 Energy balance

Heating the bitumen from 30 to 120°C requires $91 \times 0.92 \times 90 = 7.53 \text{ MJ h}^{-1}$ and heating the water from 30 to 90°C requires $108 \times 4.182 \times 60 = 27.1 \text{ MJ h}^{-1}$. In the colloid mill the slurry (116 kg, 80°C) and dispersion (100 kg, 113°C) combine; the adiabatic mixing temperature would be about 85.3°C, and the further rise to the observed 90°C outlet is supplied by dissipation of the 14.4 MJ h⁻¹ of mill shaft work, of

which about 11.7 MJ h⁻¹ is lost to the surroundings. Table 4 summarises the duties. The process requires 34.6 MJ h⁻¹ of heat and 12.06 kWh h⁻¹ of electricity, that is, about 0.22 MJ of heat and 0.077 kWh of electricity per kilogram of dry binder. The low temperatures involved (below 120°C) also reduce fume generation compared with hot-mix production [26].

Table 4
Energy balance summary (basis: 1 h)

Unit	Thermal duty or loss (MJ h ⁻¹)	Electrical energy (kWh h ⁻¹)
Bitumen storage tank	+ 7.53 (fuel)	–
Water heater	+ 27.10 (fuel)	–
Pumps (2)	–0.08 (loss)	0.06
Mixer M-1	–0.18 (loss)	2.0
Mixer M-2	–4.85 (loss)	2.0
Colloid mill	–11.67 (to surroundings)	4.0
Mixers M-3 and M-4	≈ 0	4.0
Total purchased	34.63 (fuel)	12.06

5.3 Raw-material cost

At the prices of the study (Table 5), the raw-material cost was Rs 9,503 per hour, or Rs 60.5 per kg of dry binder, compared with Rs 42.6 per kg for plain 80/100 bitumen, a ratio of about 1.4. Bitumen (41%), colourant (35%) and polymeric binder (20%) account for almost all of the cost, so the choice of colourant is the main lever for cost reduction. At a binder content of 5 wt%, the coloured binder adds roughly Rs 900 per tonne of mixture to material cost relative to plain bitumen. Utility and labour costs depend on local tariffs and plant utilisation; given the modest energy demand in Table 4, they are expected to be secondary to raw materials, but they, together with installation factors [22], must be included in a full feasibility study.

Table 5
Raw-material cost per hour at the prices of the study (Pakistani rupees, Rs)

Material	Unit price	Mass (kg)	Cost (Rs)
Bitumen 80/100	Rs 42,590.85 t ⁻¹	91	3,875.69
Filler	Rs 180 per 40 kg	9	40.50
Emulsifier	Rs 400 per 40 kg	8	80.00
Water	Rs 11.31 m ⁻³	108	1.22
Masking agent	Rs 600 per 40 kg	14	210.00
Polymeric binder	Rs 95,700 t ⁻¹	20	1,914.00
Sodium chloride	Rs 3,112 t ⁻¹	10	31.11
Colourant (dye)	Rs 670 kg ⁻¹	5	3,350.00
Total		265	9,502.52

5.4 Safety and environmental aspects

Water contact with bitumen above 100°C causes violent foaming, which is a particular concern in a process that combines hot bitumen and hot water; tanks require low-level interlocks, overflow protection and temperature control [1]. Occupational exposure to bitumen emissions should be minimised [26, 27]. Pigments containing lead, cadmium or hexavalent chromium must be excluded [10], and the chloride added in M-4 calls for corrosion-resistant materials downstream. Wash water containing emulsified bitumen, clay and colourant must be treated before discharge.

6 Limitations and further work

The experimental work was exploratory. Colour was assessed visually, and no instrumental colorimetry, solar reflectance or standard binder and mixture tests were performed. Further work should (i) replace textile dyes with inorganic pigments and optimise their dosage; (ii) quantify colour (CIELAB) and solar reflectance of the black, grey and coloured binders; (iii) characterise the emulsion (residue, droplet size, storage stability, breaking) and the recovered binder (penetration, softening point, viscosity, ageing); (iv) test mixtures for Marshall stability, indirect tensile strength, moisture sensitivity, rutting and skid resistance against a conventional reference; (v) assess colour retention under weathering and traffic; (vi) re-examine the role of sodium chloride, which may destabilise the emulsion; and (vii) update the cost estimate with current prices, tariffs and installation factors.

7 Conclusions

Direct addition of colourant to hot 80/100 bitumen, even at 7.4% of bitumen mass, darkened it only from black to dark brown, and fillers or clay mixed into continuous hot bitumen did not lighten it.

A stable bitumen-in-water emulsion was obtained by controlling water content, agitation and emulsifier type.

Adding a light mineral phase (calcium hydroxide and montmorillonite) after emulsification converted the binder from black to grey. The order of addition is decisive: the mineral must be introduced when bitumen is the dispersed phase.

The grey base could be tinted with less colourant than black bitumen. A polymeric binder restored binding capacity; colour fastness requires inorganic pigments in place of textile dyes.

A continuous process producing 265 kg h⁻¹ of coloured emulsion (157 kg h⁻¹ dry binder) requires about 0.22 MJ of heat and 0.077 kWh of electricity per kilogram of dry binder, with a raw-material cost about 1.4 times that of plain bitumen at the prices of the study. Optical masking of emulsified bitumen is therefore a promising low-cost route to coloured binders, subject to the performance testing outlined above.

Declarations

Competing interests.

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.

Use of generative AI.

This manuscript is based on the undergraduate thesis of the authors (2010). During manuscript preparation the authors used Claude (Anthropic), a generative AI tool, to restructure the thesis into article form, draft and edit text, update the literature survey and re-check the material and energy balance calculations. The authors reviewed, verified and edited all content and take full responsibility for the manuscript.

Author Contribution

H.M. conducted the conceptualisation, investigation, methodology, process design, and wrote the original draft. M.H.K. provided supervision and resources, and contributed to writing, review, and editing. Both authors read and approved the final manuscript.

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Blinded for peer review.

Data Availability

The datasets generated and analyzed during the current study are available in the Zenodo repository, <https://doi.org/10.5281/zenodo.22875779>. Additional experimental records are available from the corresponding author upon reasonable request.

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Figures

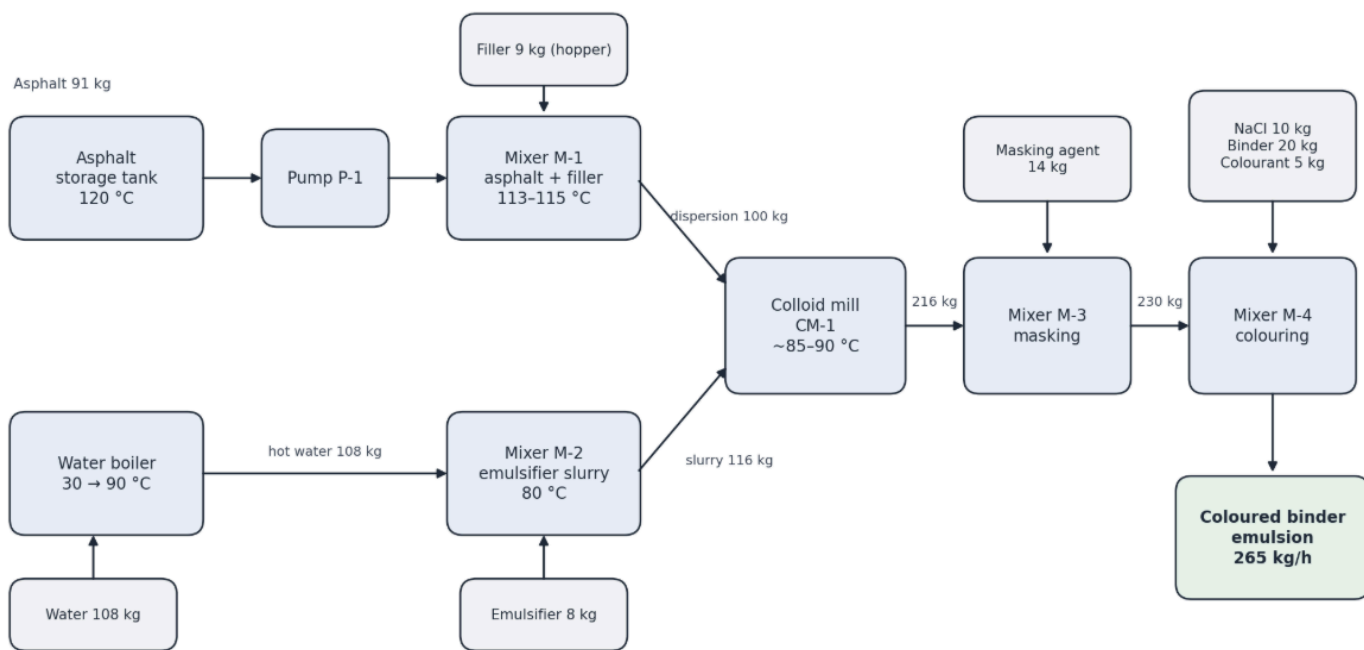


Figure 1

Process block flow diagram with mass flows (basis: 1 h of operation)