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Waste Engine Oil as a Rejuvenator and Modifier for Asphalt Binder and Evaluation of Self-Healing

Aadima M[1], Anuvrinda P P[2], Ajay Krishna K[3], Sruthimol P[4]
Department of Civil Engineering, Eranad Knowledge City Technical Campus, Manjeri, Malappuram, Kerala, India

Abstract: ***Asphalt binder does not stay the same once a road is opened to traffic. Oxygen, heat and repeated loading slowly harden it, and a hardened binder cracks far more readily than a supple one. This paper presents the first phase of an undergraduate study on waste engine oil (WEO) as a low-cost rejuvenator and modifier for aged binder, together with a simple image-based way of judging how well cracks in the binder close up again. The work reviews what has been published on WEO, points out where earlier studies disagree or fall short, and lays out a controlled laboratory plan. Aged binder recovered from reclaimed asphalt pavement (RAP) will be compared with virgin VG30 bitumen and with blends containing 0, 2, 4, 6, 8 and 10 % WEO by mass of binder. Penetration, softening point, ductility, and flash and fire point tests are planned, with Marshall stability and flow as an optional mixture-level check. Crack closure will be recorded by macro photography and measured in ImageJ. Earlier work suggests that WEO raises penetration and ductility but lowers the softening point, so an excess of oil can erode rutting resistance; additives such as SBS, crumb rubber, lignin and polyphosphoric acid are therefore considered as a counterweight. No new experimental results are reported here. The expected behaviour is stated as hypotheses for Phase II to confirm or reject.***

Keywords: asphalt binder, bitumen, waste engine oil, rejuvenator, aged binder, reclaimed asphalt pavement, self-healing, ImageJ

I. INTRODUCTION

A. Background

Most of India's highways, state roads and rural roads are flexible pavements: layers of bituminous material resting on granular base and sub-base courses. What holds the surface course together is the binder, a dark, thermoplastic residue of crude-oil refining that coats the aggregate and glues it into a load-spreading skeleton. A cement concrete slab gains strength through hydration; a bituminous mix, by contrast, depends on a binder whose stiffness swings by orders of magnitude between a cold night and a hot afternoon. That temperature sensitivity is exactly what makes the material workable at the plant and, at the same time, vulnerable on the road. The binder is also not chemically inert. From the day it is mixed and laid, it meets oxygen, sunlight, water and traffic. Oxidation converts light, mobile molecules into heavier and more polar ones, the asphaltene fraction grows, and the binder becomes stiff and brittle. Cracks that open in such a binder let water reach the layers underneath, and the damage then spreads downward. Ageing is therefore one of the main reasons why flexible pavements fail well ahead of their design life.

B. Ageing and the Need for Rejuvenation

Ageing happens in two broad stages. Short-term ageing occurs during mixing, hauling and compaction, when the binder is hot and thinly spread; long-term ageing then continues for years through slow oxidation in service. Together they reduce flexibility and the binder's ability to relax stress, and they show up on the road as fatigue cracking, block cracking, raveling and potholes.

Rejuvenation tries to reverse part of this damage by putting back what ageing removed. A suitable additive lowers viscosity, restores ductility and improves flexibility, and in doing so makes it practical to reuse reclaimed asphalt pavement (RAP), which saves virgin material, energy and money. The difficulty is that many commercial rejuvenators are themselves manufactured products with their own environmental cost. This is the opening for a waste-derived alternative.

C. Why Waste Engine Oil

Used lubricating oil from petrol and diesel engines is produced in large quantities and is hazardous if dumped or burned carelessly. Chemically, however, it is a blend of light hydrocarbon fractions that resemble the maltenes lost from bitumen during ageing. Mixed into aged binder in controlled amounts, it can soften the binder, bring back ductility and improve workability. Turning a polluting waste stream into a pavement material is attractive on both environmental and economic grounds, but only if the dosage is chosen with care, because the same softening action that rejuvenates the binder can also weaken it at high temperature.

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D. Significance of the Study

The study seeks to convert a potentially hazardous waste into a resource for sustainable road construction. If it succeeds, less virgin bitumen is consumed, material costs fall, and the environmental burden of waste oil disposal is reduced. It also examines how WEO affects both the physical properties and the crack-healing behaviour of aged binder, which bears directly on pavement durability. Because the programme relies on conventional binder tests and inexpensive image analysis, it can be carried out in an undergraduate laboratory, which keeps the approach practical and economical.

II. MATERIALS AND TOOLS

1) *Asphalt binder:* The base binder is paving-grade VG30 bitumen (IS 73:2013 [6]), the grade most often specified for surface courses on Indian highways. Bitumen is graded by its viscosity at 60 °C. Three properties describe it well enough for this work: penetration (hardness), softening point (the temperature at which it begins to flow) and ductility (how far it stretches before breaking).
2) *Waste engine oil:* The rejuvenator is used lubricating oil drained from petrol and diesel engines. Before use it is cleaned of coarse suspended matter and water so that every blend is made with a uniform material. The dosage is expressed as a percentage of binder mass and varied across the planned range. In the blend, the oil plays the part of the light, mobile fraction that ageing has depleted.
3) *Reclaimed asphalt pavement binder:* Genuinely aged binder is obtained from RAP, the material recovered when an old bituminous surface is milled or excavated. RAP is aggregate coated with binder that has already spent years oxidising, so recovering that binder gives a realistic test material on which the oil's rejuvenating effect can be observed directly. RAP also matters because recycling it is the practical route by which rejuvenated binder returns to the road.
4) *Additives:* Four additives are considered: SBS polymer, crumb rubber, lignin and polyphosphoric acid (PPA). SBS and crumb rubber are elastomeric and build an elastic network within the binder, while lignin and PPA are stiffening modifiers that lift high-temperature performance. Each will be added in controlled proportions so that its effect on the physical properties and on self-healing can be separated from that of the oil.
5) *Tools:* ImageJ, a public-domain image-processing program widely used for scientific measurement, quantifies crack closure. The macro photograph is opened, the scale is set against a reference object, and the crack is isolated by thresholding so that crack pixels are separated from the surrounding binder. The program reports the crack area, the same is done for the photograph taken after healing, and the two are compared. Since the measurement comes from the image and not from the eye, it is repeatable and free from the subjectivity of visual estimation. Microsoft Excel is used to tabulate penetration, softening point, ductility and Marshall values and to plot them against dosage, so that trends such as dosage versus penetration or dosage versus healing efficiency are visible at a glance and the optimum can be located.

III. OBJECTIVES AND SCOPE

A. Objectives

The study has five objectives:

- to evaluate how WEO dosage changes the physical properties of neat and aged binder, using the standard penetration, softening point, ductility, and flash and fire point tests;
- to improve the high-temperature performance of WEO-modified binder by combining the oil with additives such as SBS, crumb rubber, lignin or PPA;
- to quantify the self-healing efficiency of the modified binder by digital analysis of crack area before and after a controlled thermal healing cycle;
- to find an optimum WEO dosage that balances rejuvenation against pavement performance, for sustainable and cost-effective construction; and
- to judge the potential of WEO as a sustainable outlet for a polluting waste stream in asphalt pavements.

B. Scope

The work covers WEO as a rejuvenator for aged binder and its influence on flexibility, workability and high-temperature behaviour at several dosages, including the use of additives to make up for any loss of rutting resistance. Self-healing is assessed by macro imaging and ImageJ analysis of crack closure, and an optimum dosage is sought. The study is limited to laboratory-scale binder testing, with mix testing as an option. Long-term field performance, full-scale construction trials and a detailed economic analysis lie outside it and are listed as further work.

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IV. LITERATURE REVIEW

A. Previous Studies

Mortier and Nahar [1] reviewed bitumen extension with waste-oil products, namely re-refined engine oil bottoms (REOB) and vacuum tower asphalt extender (VTAE). They saw promise in cutting dependence on petroleum-based material, but flagged variable composition, ageing behaviour, phase stability and the risk of exudation. An important caution follows from their work: REOB and VTAE are processed products, not raw used oil, so their findings cannot be carried over to WEO without testing.

Mehmood *et al.* [2] surveyed WEO as an asphalt rejuvenator and modifier. Their review reports that WEO lowers the viscosity and stiffness of aged binder while raising penetration and ductility, but that it also lowers the softening point and can hurt rutting resistance. Several of the studies they cover found that roughly 4–7 % WEO restored aged binder, although the authors stress that this range is not universal and depends on the aged binder and the degree of rejuvenation wanted. The review also notes that WEO improves low-temperature flexibility and can ease fatigue cracking at intermediate temperatures, and it points to lignin, crumb rubber and SBS as ways of recovering high-temperature stiffness.

Banerji *et al.* [3] blended 1–5 % waste cooking oil (WCO) and WEO into VG40 bitumen and short-term aged the samples in the thin film oven test (TFOT). Penetration, softening point, viscosity, ductility, penetration index and penetration ageing ratio were measured. Both oils raised penetration and ductility and lowered softening point and viscosity, with WEO having the stronger effect. Contents up to about 3 % gave favourable changes, and viscosity results suggested that up to 4 % would keep the binder within its grade. Larger amounts changed the binder enough to threaten its original grade.

Nakka *et al.* [4] looked at partial replacement of VG30 bitumen by WEO in bituminous concrete at 0, 8, 12, 16, 20 and 24 % by binder mass. Penetration climbed from 58 to 88 (in 0.1 mm units) and ductility from 25 cm to 105 cm, while the softening point fell from 50 °C to 34 °C. Marshall stability dropped from 17.62 to 14.54 and flow rose from 3.4 to 5.10. In short, the mix became more flexible and workable but less able to resist deformation. These replacement levels are far larger than the rejuvenation doses discussed above, so the study is better read as a statement of the trade-off than as a dosage guide.

Sudibyo *et al.* [5] worked with low-density polyethylene (LDPE), not oil, at 2–10 % by binder mass, using penetration, ring-and-ball softening point and rotational viscometer tests. LDPE lowered penetration and raised softening point and viscosity, and recycled LDPE did so more strongly than virgin LDPE. At 8 % and above, viscosity became too high for comfortable mixing and placing. The study matters here as a mirror image: LDPE stiffens the binder, whereas WEO is meant to soften it, and both show how quickly a modifier can push workability out of bounds.

TABLE I
SUMMARY OF REVIEWED STUDIES

Study	Material and dosage	Main reported effect
[1] Mortier and Nahar (2025)	REOB / VTAE (review)	Potential to extend bitumen; concerns over composition, stability and exudation
[2] Mehmood *et al.* (2024)	WEO (review); about 4–7 % often reported	Higher penetration and ductility, lower softening point; rutting risk at high dosage
[3] Banerji *et al.* (2022)	WEO and WCO, 1–5 %, VG40, TFOT	Softer, more workable binder; about 3–4 % favourable
[4] Nakka *et al.* (2024)	WEO replacement, 0–24 %, VG30	Penetration 58 to 88, ductility 25 to 105 cm, softening point 50 to 34 °C; Marshall stability falls
[5] Sudibyo *et al.* (2024)	Virgin and recycled LDPE, 2–10 %	Stiffer binder; 8 % and above too viscous

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B. Research Gaps

Reading these studies together reveals several gaps. First, there is no agreed optimum WEO dosage; reported values run from about 3 % to well over 20 % depending on binder grade, oil source and whether the goal is rejuvenation or replacement. Second, simple image-based methods for judging self-healing of waste-oil-modified binder are rarely used. Third, the long-term durability of such binders is not well understood. Fourth, waste oil varies from source to source, so results are hard to compare. These gaps motivate the experimental programme below. The effect of WEO is also expected to depend on the composition of the oil, its dosage and its compatibility with the aged binder, which is why several dosages will be tested and compared with both fresh and aged binder.

V. PROPOSED METHODOLOGY

A. General Plan

The programme is an experimental comparison of aged binder modified with different proportions of WEO. Virgin binder of the same or a comparable grade serves as a reference where it can be obtained, and aged binder with no oil is the principal control. Work proceeds in four stages, summarised in Fig. 1: establish material identity and baseline properties, prepare the blends, run the planned tests, and compare the results while examining crack closure under a controlled thermal-healing procedure. The first step of all is to gather journal papers, reviews, standards and technical reports and to record their key findings on dosage, performance and limitations.

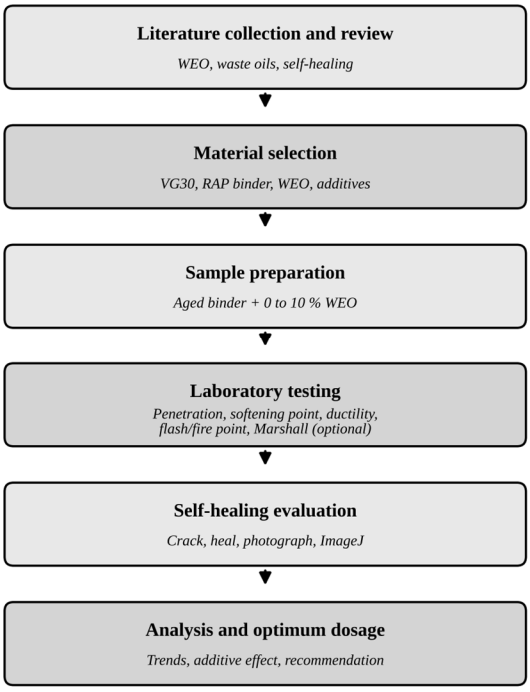


Fig. 1 Flow chart of the proposed experimental programme

B. Material Preparation and Blending

The VG30 binder is procured and its properties verified, the RAP is collected and its aged binder recovered, the oil is collected and cleaned, and the additives are procured. The quantity and quality of each material are recorded so that tests can be repeated. Blending then follows six practical rules. (1) Inventory the virgin binder, aged binder and WEO, and record mass and source before any heating. (2) Warm the aged binder at the laboratory-approved temperature until it mixes uniformly, avoiding prolonged heating, smoke or repeated overheating. (3) Weigh WEO as a percentage of aged-binder mass and add it gradually, using the same mixing time, temperature and method for every dosage. (4) Where a laboratory mixer exists, note its type and speed; if only hand mixing is approved, keep the duration and technique as uniform as possible and acknowledge this as a limitation. (5) Prepare enough material for replicate tests, pour it into labelled containers, and note the date, actual masses and any visible separation. (6) Condition the samples as each test method requires, and prepare fresh replicates if a preparation error or contamination is suspected.

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C. Laboratory Testing

The physical properties of every blend are measured by the tests in Table II. Penetration indicates consistency, softening point the temperature response, and ductility the stretch before breaking. Flash and fire points are included because the binder must be heated safely during blending and mixing, and oil-rich blends may behave differently from neat bitumen. Marshall stability and flow are optional and apply only if a full mix programme can be supported.

TABLE II
PLANNED LABORATORY TESTS

Test	Property examined	Method
Penetration	Consistency or relative hardness	IS 1203:1978 [7]
Softening point	Temperature-related softening response	IS 1205:1978 [8]
Ductility	Elongation before breaking	IS 1208 (Part 1):2023 [9]
Flash point	Temperature at which vapour ignites momentarily; safety in heating	IS 1209:1978 [10]
Fire point	Temperature at which burning is sustained	IS 1209:1978 [10]
Marshall stability and flow (optional)	Mixture-level response	ASTM D6927 [11]

D. Self-Healing Evaluation

A repeatable binder specimen or thin film is prepared for each selected dosage and labelled. A controlled crack or opening is made by an agreed method, and the crack is photographed with fixed camera distance, focus, scale and lighting. The specimen is then held at a defined thermal-healing condition, with temperature and duration recorded and kept identical for all samples. The same region is photographed again, and ImageJ is used to isolate the crack and measure its area before and after treatment. The healing percentage is calculated from

$$H\,(\%) = (A_b - A_a) / A_b \times 100 \qquad (1)$$

where A_b and A_a are the crack areas before and after healing. The result will be reported as visual crack-area closure; it will not be described as full recovery of mechanical strength, because a closed crack on the surface does not prove that stiffness or fatigue life has returned.

E. Analysis and Optimum Dosage

Test results and healing values are plotted against WEO dosage, and the trends are compared with those reported in the literature. The optimum is the dosage at which the aged binder regains acceptable flexibility and workability, keeps adequate high-temperature performance, and shows good self-healing. The role of the additives is judged by comparing blends that contain them with blends that do not, and the optimum is stated together with the additive that supports it best. Importantly, the optimum will be chosen from the measured data and the applicable specifications, not simply as the dosage that gives the highest penetration or ductility, since those values alone do not guarantee good pavement performance.

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VI. EXPECTED RESULTS

Because Phase I contains no laboratory data, the following points are hypotheses drawn from the literature and from the mechanism of rejuvenation. They will be checked against the Phase II results; a result that contradicts them is as valuable as one that confirms them.

1) Penetration and ductility of aged binder should increase with WEO dosage while the softening point falls, restoring flexibility and workability.
2) Rutting resistance at high temperature may decrease at higher dosages, since the light oil reduces elastic stiffness.
3) Low-temperature and fatigue cracking resistance should improve, because a more flexible binder tolerates thermal and traffic strain.
4) Self-healing efficiency should rise with dosage, since a softer binder has greater molecular mobility and closes cracks more readily during a thermal cycle.
5) An optimum dosage is anticipated in the range of 4 to 10 % by mass of binder, where flexibility and workability return without unacceptable loss of high-temperature performance.
6) At dosages beyond about 15 %, which lie above the planned range, the binder is expected to become too soft and too moisture-sensitive to be serviceable.
7) A suitable additive (SBS, crumb rubber, lignin or PPA) should restore high-temperature stiffness and allow a higher WEO dosage without loss of rutting resistance.

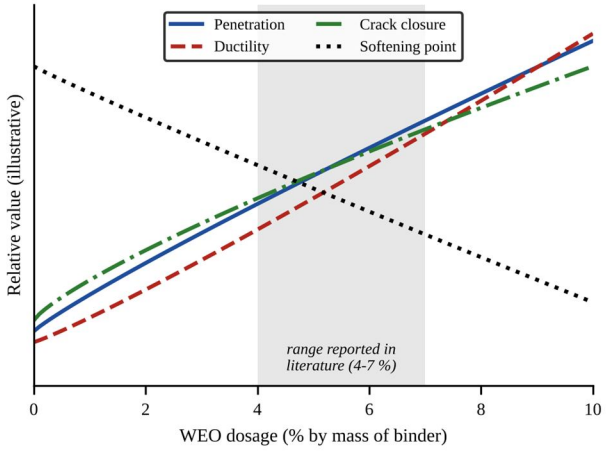


Fig. 2 Schematic of the hypothesised trends with WEO dosage. The curves are illustrative only and are not experimental data; the shaded band marks the 4–7 % range often reported in the literature [2]

VII. LIMITATIONS AND FUTURE WORK

The present study is limited to laboratory binder testing and, if resources permit, mixtures. Hand mixing, if it is the only option, may add variability, and the visual healing measure shows closure of a surface crack and not recovery of strength. Several directions follow naturally.

1) *Optimising oil content:* Further work can refine the dosage by testing more levels and comparing each with fresh and aged binder. The aim is an amount that improves flexibility and workability without sacrificing strength, since excess oil softens the binder and invites rutting.
2) *Additives for high-temperature performance:* SBS, crumb rubber, lignin or other modifiers can be added to WEO-treated binder and compared against fresh binder, aged binder and WEO-only blends. Compatibility with the oil and suitable blending conditions should be studied alongside, with the goal of a binder that combines rejuvenation with resistance to rutting.
3) *Detailed self-healing study:* Healing temperature, healing time and WEO dosage can be varied systematically, and repeated damage-and-heal cycles can show whether the binder keeps its healing ability. It also needs to be established whether better visual closure corresponds to recovery of mechanical performance.
4) *Moisture resistance:* Oil may change the bond between binder and aggregate. Mixtures with different dosages should be compared with conventional mixtures for aggregate coating, adhesion and resistance to water damage, so that rejuvenation does not come at the expense of wet-weather durability.

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5) *Long-term ageing and durability:* Short-term and long-term ageing procedures can be applied, with penetration, softening point and ductility measured before and after, to see how treated binder ages compared with fresh and untreated aged binder.
6) *Marshall mix properties:* Binder tests do not on their own establish mixture performance. Marshall stability, flow, bulk density and volumetric properties of mixes with different dosages should be compared with a control mix.
7) *Standardised procedure:* Oil composition, blending temperature, mixing time and dosage all influence the result. A controlled preparation and testing procedure, with repeated tests and comparison of different oil sources under identical conditions, would make results comparable. Any proposed procedure should be validated against relevant standards before it is recommended for practice.

The long-term aim is a technically reliable, durable and environmentally responsible way of rejuvenating aged bitumen with waste engine oil.

VIII. CONCLUSION

Oxidative ageing stiffens and embrittles asphalt binder and leads to cracking and premature failure. The reviewed literature indicates that waste engine oil, rich in light hydrocarbons, can restore properties of aged binder by replenishing the depleted maltene-like fractions, but that excess oil reduces rutting and moisture resistance, a weakness that additives may offset. The main gaps are the lack of a consensus dosage, the limited use of simple image analysis for judging self-healing, and the uncertain long-term durability of such binders.

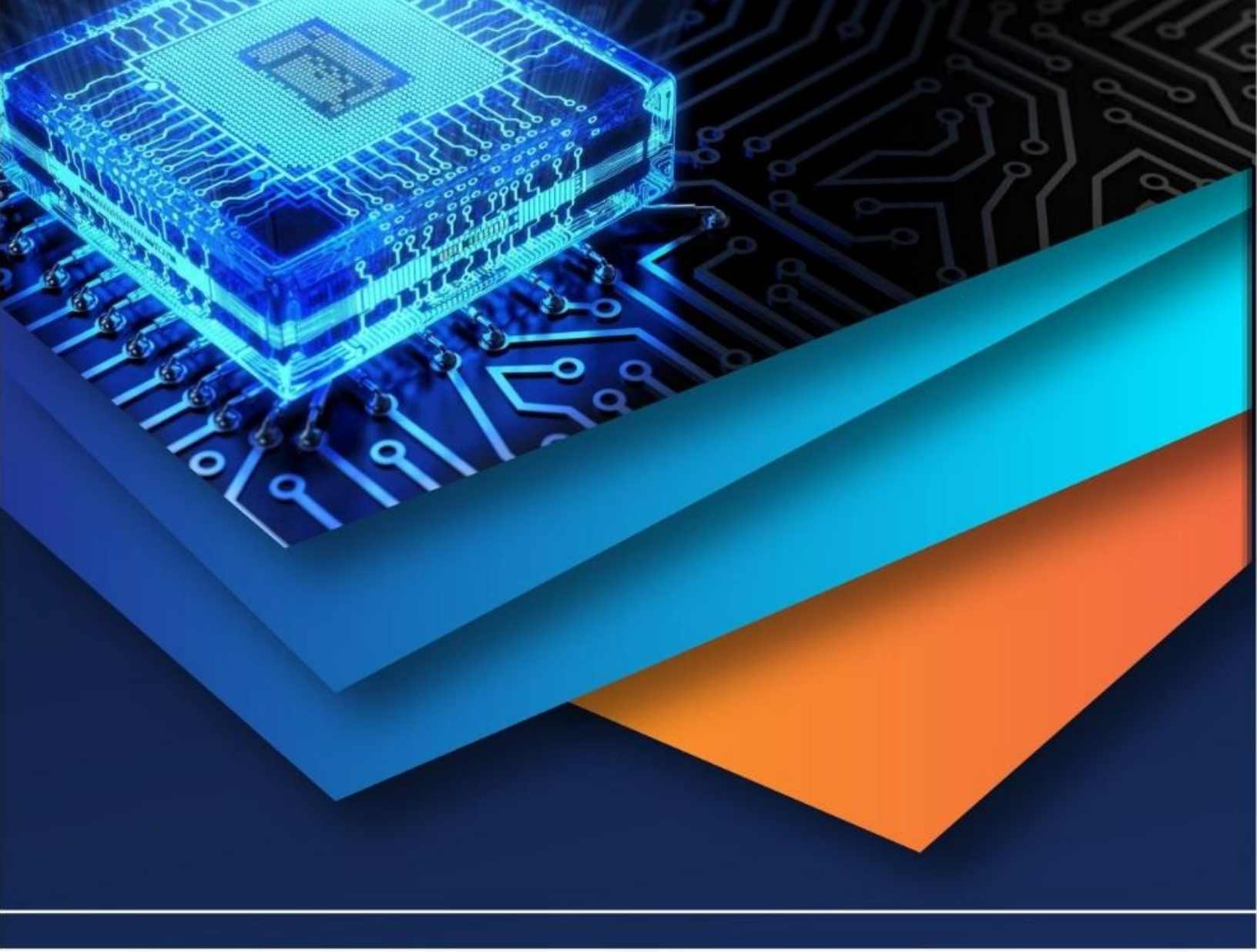
Based on this review, objectives, scope and a methodology have been defined, together with a programme of standard tests: penetration, softening point, ductility, flash and fire point, optional Marshall testing, and an ImageJ-assisted crack-healing trial. A dosage of about 4 to 10 % by mass of binder, possibly combined with an additive, is anticipated to give the best balance of workability, flexibility, durability and high-temperature performance. This remains a hypothesis. Phase II will procure the materials, prepare the blends, carry out the tests, identify the optimum dosage and quantify self-healing, and will then judge the technical, economic and environmental viability of waste engine oil in asphalt pavements.

IX. ACKNOWLEDGMENT

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