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Article

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Experimental and Life Cycle assessment of RAP modified with Fe_2O_3 and Waste Cooking Oil Admixtures

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Abstract

Thermal cracking, rutting, and moisture damage are common pavement distresses caused by heavy traffic growth, construction deficiencies, and environmental effects, reducing service life and performance. Asphalt additives can improve pavement behavior; however, a single modifier rarely enhances all properties simultaneously. This study investigates a composite modification approach using dual additives in reclaimed asphalt pavement (RAP). Five mixtures were evaluated: control mix, RAP mix, RAP with waste cooking oil (WCO), RAP with nano Fe2O3, and RAP with a composite of WCO and nano Fe2O3. Marshall immersion, low-temperature splitting, and wheel tracking tests were conducted to assess moisture resistance, thermal cracking, and rutting performance. Environmental performance was evaluated using life cycle assessment (LCA) with SimaPro software. Results indicate that nano Fe_2O_3 improved rutting resistance and moisture stability, while WCO enhanced low-temperature cracking resistance. The composite-modified mixture achieved the best overall mechanical performance. Environmentally, RAP modified with nano Fe_2O_3 showed the lowest impacts.

Keywords: Asphalt Mixes, RAP, Life Cycle Assessment (LCA), Nano Fe_2O_3, WCO; laboratory evaluation

1. Introduction

In the dominion of road construction, asphalt mixes are the fundamental component that keeps the transportation system running smoothly and dependably [1]. Consequently, asphalt mixes are frequently utilized in road construction due to their superior binding properties, water resistance, and durability capability [2-3]. Nevertheless, ordinary asphalt mixes susceptible to such distresses as thermal cracking at low temperatures, rutting at high temperatures, and aging with time [4]. Numerous modifiers have been investigated to improve the sustainability and performance of asphalt mixtures to meet these restrictions.

A potentially effective method is adding nanomaterial to asphalt mixtures. Because of their distinct physicochemical characteristics and high surface area-to-volume ratio, nanoparticles can greatly enhance the mechanical and physical characteristics of asphalt mixes. Of all the nanomaterial, nano-Fe_2O_3 (magnetite nanoparticles) has drawn the most interest because of its great thermal stability, cheap cost and toxicity, and capacity to enhance the mechanical qualities and aging resistance of asphalt mixes [5].

Additionally, as a practical and affordable tactic, the utilization of waste materials in asphalt alteration has gained popularity. Because it is readily available, inexpensive, and can improve the rheological characteristics of asphalt binders, waste cooking oil (WCO) is a viable option for asphalt modification [6-7]. Triglycerides and fatty acids included in WCO can interact with the asphalt binder to change its chemical makeup and enhance certain performance attributes [8].

Furthermore, the usage of RAP gains more attention these days due to its benefits as eco-friendly materials and preservation of natural raw materials, and the addition of RAP into asphalt mixture has shifted towards sustainable green technologies.

Using nano-Fe_2O_3 and WCO together as asphalt mixture modifiers presents a special chance to take benefit of the advantages of both waste materials and nanomaterial. While WCO can improve the rheological characteristics and perhaps increase the workability and sustainability of the asphalt mixture, nano-Fe_2O_3 incorporation can improve the durability of asphalt binders, mechanical

properties, and aging resistance. Furthermore, the road industry uses a variety of raw materials, including sand, aggregates, filler, bitumen, and selected types of additives, all of which require a significant amount of energy and natural resources to extract, manufacture, process, and transport. This industry contributes significantly to the pollution of the soil, air, and water in the surrounding areas [9]. Also, these emissions occur during the raw materials manufacturing, extraction, and transportation, as well as during the manufacturing of asphalt mixes and the construction processes of wearing surfaces. Several LCA research have recently addressed the environmental implications of road construction procedures around the world, but there are still a few issues that need to be investigated further.

This research seeks to investigate the performance of RAP asphalt mixtures modified with nano-Fe_2O_3 and WCO through a comprehensive experimental study. The effects of each modifier on the mechanical properties of the asphalt mixture will be evaluated through carried out Marshall, wheel loading tracking, Marshall Immersion, and indirect tensile strength tests. In addition, the possible synergistic effects of mixing these two modifiers will be investigated in order to create asphalt mixtures for road construction applications that are both high-performing and sustainable. In addition, this research aims to contribute significantly to environmental evaluation by comparing the environmental effects of road construction using selected modified asphalt mixtures in Egypt, based on a LCA. This input will be beneficial in the planning and management of long-term road development. The environmental implications of road construction are measured, including the extraction and manufacturing of binders, additives and materials, as well as the manufacturing of bituminous mixes, transportation of materials and bituminous mixes, and wearing surface construction. Therefore, the environmental effects associated with the categories of ADP, AP, EP, GWP, OLD, HTP, FWETP, METP, TETP, POFP are assessed depending on the CML2001 impact assessment approach. These outcomes will play a significant role in supporting government and industry decision-makers in developing the policies and management strategies of road construction, in addition to assessing investments in the facilities of the new road building.

1.1. Literature Review

Current research focuses on incorporating recycled asphalt pavement (RAP), nano ferric oxide (Nano Fe_2O_3) and waste cooking oil (WCO) into asphalt mixtures. By leveraging the unique characteristics of these additives, scholars aim to improve the mechanical performance and sustainability of asphalt mixtures. Existing literature has separately investigated asphalt systems modified by RAP, WCO, Nano Fe_2O_3 or their binary combinations, yet no laboratory research has reported the composite modification of RAP asphalt mixtures with both WCO and Nano Fe_2O_3. Meanwhile, numerous life cycle assessment (LCA) studies worldwide have analyzed the environmental burdens generated during road construction, and several research gaps remain to be further explored. The core findings and insights from previous relevant studies are sorted and discussed as follows.

RAP recycling delivers prominent economic and environmental benefits. Statistics from [9] indicate that over 100 million tons of RAP are recovered for reutilization in the United States each year, saving more than 61.4 million cubic yards of landfill space, which greatly promotes the application prospect of recycled asphalt technology.

Filho et al. (2020) [10] prepared cold-recycled bituminous mixtures with 100% RAP content, and test results proved that full RAP incorporation significantly improved the comprehensive performance of cold-recycled asphalt mixtures. Al-Ghurabi and Al-Humeidawi (2021) [11] proposed an optimized aggregate gradation scheme: replacing 20% RAP with fine aggregates and setting the proportion of coarse aggregates to 40% of the total aggregate mass can effectively enhance mixture properties, and they also verified the feasibility of applying RAP to hot-mix asphalt.

Different studies have drawn inconsistent conclusions regarding the performance of asphalt mixtures with varying RAP contents. Colbert and You (2012) [12] found that recycled asphalt mixtures with low RAP ratios possess strong resistance to moisture damage. However, Bennert and Maher (2005) [13] pointed out that high dosages of recycled aggregates will reduce the CBR value and bearing capacity of mixtures, and they recommended that the mixing ratio of recycled aggregates and virgin aggregates should not exceed 50%. In contrast, Naser et al. [14] found that asphalt mixtures modified with 75% RAP achieved the maximum Marshall stability, demonstrating that RAP can strengthen the structural stability of mixtures. Some scholars further explored the collaborative blending of RAP and recycled coarse aggregates (RCAs). Fournier et al. (2020) [15] mixed the two types of solid waste into asphalt

mixtures, and their results confirmed that the new composite pavement material can drastically cut the consumption of natural aggregates with outstanding environmental advantages. Pradhan and Sahoo (2021) [16] adopted a compound modifier consisting of 60% RCAs and longifolia oil; the target service performance of mixtures was realized without obvious deterioration of pavement functionality.

The regulating effect of WCO on the elastic properties of asphalt is highly correlated with the chemical composition of asphalt binders. Maharaj et al. (2015) [17]and Singh-Ackbarali et al. (2017) [18] derived consistent rheological rules through tests: the phase angle of neat petroleum asphalt blended with WCO gradually decreases with the growth of WCO dosage, while the phase angle of rock asphalt modified asphalt rises continuously as WCO content increases. Interestingly, the phase angle of asphalt modified by WCO composite additives presents a trend of decreasing first and then increasing. Azahar et al. (2016) [19] revealed that the interfacial bonding force between WCO and asphalt binders dominates the modification effect of WCO on asphalt performance. Strengthened interfacial bonding between pretreated WCO particles and asphalt matrix simultaneously improves the softening point, viscosity, rutting resistance and anti-aging index of blended asphalt. In another piece of research completed by Azahar et al. (2016) [19], orthogonal design was adopted to optimize the dosage and preparation parameters of WCO residue for rubber asphalt modification. WCO residue facilitates the swelling and fragmentation of rubber particles, which optimizes the storage stability of rubber asphalt and enhances its anti-aging capacity. Moreover, WCO residue increases the proportion of lubricating phase and reduces the contact area between crumb rubber and asphalt. Eriskin et al. [20] conducted experiments with waste frying oil as modifier, and the results showed that waste oil lowers the softening point and raises the penetration of asphalt binders, making such modified asphalt suitable for cold-region pavement construction. Wang et al. (2019) evaluated the aging characteristics of various asphalt binders and verified that bio-oil derived from WCO optimizes the colloidal dispersion system of modified asphalt and offsets aging-induced performance degradation. When 5%, 10% and 15% WCO were separately added into SBS-modified asphalt and 70# base asphalt, the failure stress of modified asphalt declined, while fatigue life and failure strain at moderate temperatures increased. Additionally, the yield energy of modified asphalt continuously dropped with the rising WCO content [21]. Multiple studies have proven that WCO can serve as an anti-aging agent for aged asphalt. Gökalp and Uz (2019)

discovered that WCO substantially reduces the softening point, viscosity and rutting factor of asphalt. Liu et al. [28] reported that WCO improves the storage stability of asphalt jointly modified by SBS and EVA, and the compatibility between SBS and EVA reaches the optimal state at a WCO dosage of 10%. Li et al. [23] determined the optimal WCO dosage of 4% for epoxy asphalt binders based on comprehensive indicators including viscosity, microstructural characteristics, damping performance and mechanical properties. WCO addition extends the construction time window of modified asphalt, elevates its damping behavior and elongation at break, and reduces binder viscosity as well as the particle size of dispersed phases. Meanwhile, the base asphalt type, WCO dosage and WCO quality all exert significant influences on the final modification performance of asphalt.

Research on asphalt modified by Nano Fe_2O_3 Nano Fe_2O_3 can comprehensively upgrade the mechanical performance of asphalt concrete via nano-size effect. Miguel and Crucho (2018) [24] modified AC 14 asphalt concrete with 4% nano iron; granite aggregates and limestone filler were used in mixtures, with 35/50 grade asphalt as the control binder and a fixed binder content of 4.5%. After modification, the retained Marshall stability rose from 77% to 80%, the indirect tensile strength ratio increased from 57% to 82%, and permanent deformation was reduced by 20% compared with the reference mixture. Two independent experimental studies drew identical variation rules regarding the optimal dosage of Nano Fe_2O_3: the performance of asphalt mixtures first rises and then declines with the increase of nano-material dosage, with a unique optimal mixing proportion. Pirmohammad et al. (2020) [25] adopted 60/70 grade asphalt (PG 64-22) as the base binder and set four Nano Fe_2O_3 dosages of 0.1%, 0.4%, 0.8% and 1.2%. Semi-circular bending (SCB) tests were applied to characterize the fracture performance of mixtures. The fracture resistance achieved a 27% increment at the dosage of 0.8%, and further dosage growth led to weakened fracture toughness. Kordi and Shafabakhsh (2017) [26] evaluated the mechanical properties of asphalt mixtures modified by 0.3%, 0.6%, 0.9% and 1.2% Nano Fe_2O_3, and the optimal modification effect appeared at 0.9% dosage. At this dosage, the stiffness modulus increased by 28%, 14% and 45% at 5 ℃, 15 ℃ and 25 ℃ respectively; permanent deformation at 60 ℃ decreased by 18%, and fatigue life was improved by 15%-35% depending on ambient temperature and stress magnitude.

Life cycle assessment (LCA) is a mainstream method to quantify the full-life environmental load of asphalt pavements. Existing literature has carried out environmental impact comparisons among hot-mix asphalt (HMA), warm-mix asphalt (WMA), recycled aggregate asphalt and nano-modified asphalt mixtures. Ma et al. (2019) [27] applied the LCA framework to evaluate the environmental impacts of HMA and WMA mixtures. Their results suggested that the total lifetime resource consumption of WMA and HMA pavements is roughly equivalent. HMA pavements generate slightly higher environmental burdens related to PM2.5 emissions and greenhouse gases, except under long-term service conditions where HMA exhibits better environmental performance. Vega-Araujo et al. (2020) [28] compared the environmental footprint of WMA with RCA as partial replacement of natural aggregates (NA) and conventional HMA without RCA. The replacement of coarse NA by RCA deteriorated the environmental performance of WMA mixtures, which can be explained by the weaker mechanical capacity of WMA-RCA mixtures, requiring thicker pavement layers during construction. Sackey et al. (2019) [29] established an LCA model for nano-modified asphalt mixtures (NMAM) based on material output emissions, and compared the environmental contribution of nano-silica with ordinary asphalt mixtures. The global warming potential (GWP) of NMAM reached 7.45×10^3 kg CO_2-equivalent per functional unit, while the value of conventional asphalt mixtures was 7.42×10^3 kg CO_2-equivalent. Martinez-Arguelles et al. (2019) compared the environmental loads of virgin coarse NA production and composite aggregates mixed with RCA and NA. The LCA results indicated that the transportation distance from limestone raw material sites to mixing plants is the dominant factor affecting the environmental performance of RCA-NA aggregates, and the transportation distance of raw materials should be controlled within 200 kilometers. Shi et al. [30] conducted a comparative analysis on the economic and environmental burdens of Portland Cement Concrete (PCC) pavements with RCA and conventional PCC pavements. The application of RCA brings environmental benefits during the production and construction stages of PCC pavements, yet it triggers stronger adverse environmental impacts in the service period. A series of LCA studies focusing on modified asphalt mixtures have also drawn distinct conclusions. Boraie et al. (2024) [31] adopted LCA tools to analyze the environmental impacts of asphalt mixtures co-modified by RAP and waste polyethylene. Compared with unmodified base mixtures, this composite modified system produces the lowest environmental impacts on human

192 health, natural resources and ecosystems. Yue et al. (2022) [32] completed a comparative LCA on
193 asphalt mixtures modified by diatomite powder and lignin fiber, and pointed out that modified mixtures
194 only generate minor negative environmental impacts relative to control groups. Khater et al. (2021) [33]
195 studied asphalt mixtures modified by glass and lignin fiber, and their test data proved that the combined
196 addition of the two fibers brings higher environmental burdens than neat asphalt mixtures.

197 Synthesizing the above domestic and international literature, scholars have separately explored the
198 mechanical properties of asphalt mixtures modified by single RAP, single WCO or single Nano Fe_2O_3,
199 and assessed the environmental impacts of various recycled and modified pavement materials through
200 LCA approaches. Nevertheless, to the best of the authors' knowledge, no existing research has
201 simultaneously adopted WCO and Nano Fe_2O_3 to composite-modify RAP asphalt mixtures, nor
202 systematically quantified the mechanical performance and full-life environmental load of such dual-
203 modified systems. Against this background, this study adopts a dual-addition modification technology
204 to synergistically exert the unique advantages of WCO and Nano Fe_2O_3. Without compromising long-
205 term pavement service performance, this technology can simultaneously optimize the overall
206 mechanical properties and environmental sustainability of RAP asphalt mixtures.

207 ## 2. Materials

208 ### 2.1. Virgin Bitumen

209 In the current study, asphalt binder with grade 60/70 was chosen as a type of virgin bitumen for heavy
210 traffic loads, as per the Egyptian specification. Table 1 summarizes the properties of the virgin bitumen
211 used in this research.

212 **Table 1. Characteristics of the virgin bitumen**

Test No.	Test	Designation No.	Values	Specification limits
1	Penetration test (0.1 mm)	AASHTO-T49	62	60-70
2	Density (15°C) (g/cm^3)	AASHTO-T228	1.026	------
3	Softening Point (°C)	AASHTO-T 53	47	45-55
4	Flash point (°C)	AASHTO-T48	275	+250
5	Kinematics viscosity (cSt)	AASHTO-T201	425	+320
6	Ductility (cm)	AASHTO-T 300	+100	≥ 95

213

214

2.2. Aggregate and gradation

2.2.1 Aggregate and filler powder

Limestone was used in this study for the coarse and fine aggregates, which acquired from Ataka quarry, Suez Government, Egypt. Water absorption value, Los Angeles, crushing value, and apparent specific gravity value were calculated as essential characteristics. The properties of the coarse (Agg.1 & Agg.1) and fine aggregates (sand) are listed in Table 2, based on the Egyptian specification. Furthermore, crushed limestone was selected as a mineral powder, which has an apparent specific gravity of 2.75.

Table 2. Coarse and fine aggregate characteristics.

Test No.	Test	Designation No.	Values			Specification limits
			Agg.1	Agg.2	Sand	
1	Apparent specific gravity.	AASHTO T-85	2.716	2.716	2.671	N/A
2	% absorption	AASHTO T-85	2.90	2.30	3.20	≤ 5
3	Los angles abrasion test %	AASHTO T-96	22.6	23.1	---------	≤ 40
4	Stripping Test	AASHTO T-182	> 95	> 95	---------	≥ 95

2.2.2 Gradation of the Mixture

This study used the gradation of 4C, based on Egyptian specification. The gradation of the mix design (4C) used are displayed in Figure 1, and the selected gradation is within the limits.

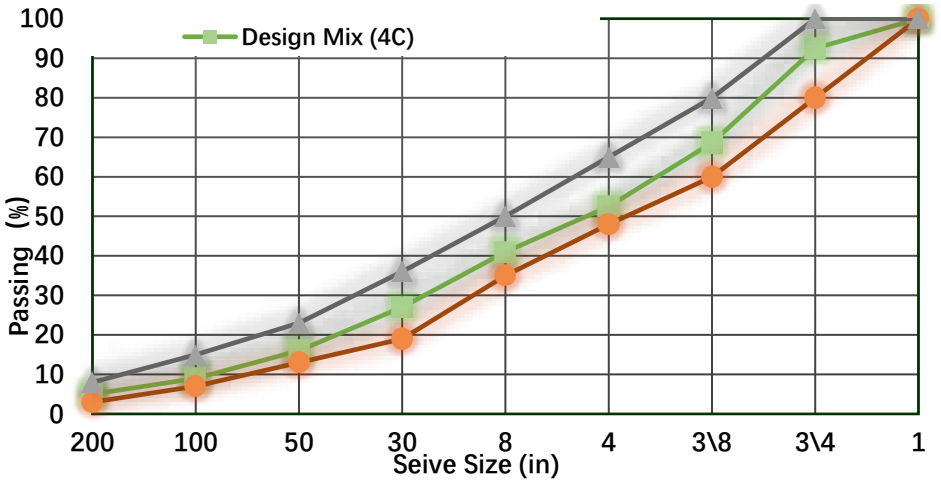


Figure 1. Selected bituminous mix aggregate gradation (4C)

2.3. Additives

RAP, Nano Fe_2O_3 and WCO were selected as sustainable materials among various types of additives in order to enhance the performance of the adjusted asphalt mixes. RAP as shown in Figure 2 was

collected from urban road in Zagazig, Sharqia Government, Egypt. Table 3 displayed the gradation and bitumen content of RAP that was computed based on centrifuge extraction test. Figure 3 presented the two additives used in modifying asphalt mix. Nano Fe_2O_3 was manufactured in Benha Faculty of Science, Benha University, Egypt. The morphology and diameter distribution of Nano Fe_2O_3 are presented in Figure 4. While WCO was gotten from the residual vegetable oil that was used in frying food with a specific gravity of 0.75 and flash point of 205 ^{0}C. The SEM of WCO is clarified in figure 5.



Figure 2. RAP sample and centrifuge extraction equipment

Table 3. Gradation and bitumen content in RAP sample

Sieve size (in)	1	3\4	3\8	No. 4	No. 8	No. 30	No. 50	No. 100	No. 200
RAP (Passing %)	100	97.60	84.50	61.30	49.50	32.60	16.30	8.50	4.80
RAP Bitumen %					3.80				

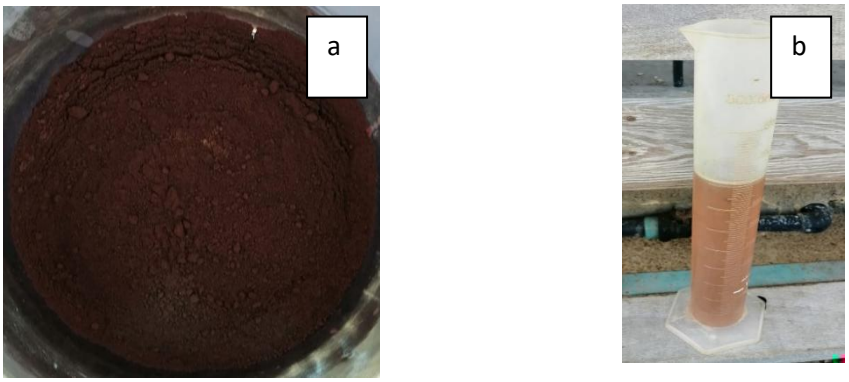


Figure 3. Types of Additives used in current study: (a) Nano Fe_2O_3, (b) WCO

Figure 4 displays a SEM image of iron oxide nanoparticles that were manufactured. It demonstrates the rough surface and the nearly spherical-shaped particles that are visible in the morphology. To ascertain particle size, a number of particles were examined. It is evident that the sample is made up of

nearly spherically shaped and evenly distributed particles. The particles range in size from approximately 23 nm to 55 mm. It is clear that this goethite aggregate is made up of (a) rod bundles, (b) large, thin rods, and (c) plate-like particles that may be shattered pieces of large, thin rods. The diameter of the bundles of goethite rods ranges from 25 to 45 nm. The coated sand has microspores and may have a high specific surface area as a result of iron oxide nanoparticles depositing on the sand surface.

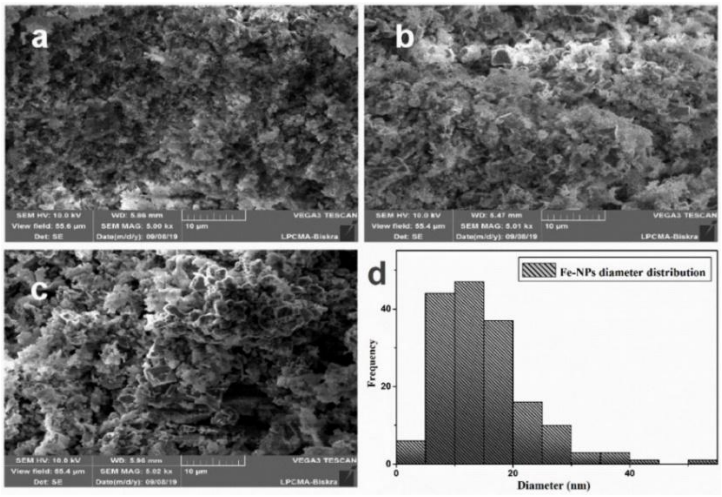


Figure 4. SEM and diameter distribution of Nano Fe_2O_3

The morphology of the structures existing in asphaltenes was examined, through applying SEM technique. A SEM image of C1-RC asphaltenes is presented in Figure 5(a and b), displaying a flaky soft solid with precipitated agglomerates over the surface. The solubility of resin in crude oil asphaltenes can be the reason for the presence of these agglomerates. A SEM micrograph of C2-RM asphaltenes is provided in Figure 5 (c and d). It reveals a more granulated flaky surface with a higher precipitation and agglomeration degree, along with the unevenly dispersed holes and voids. The creation of pores and cavities is a result of the resinous materials that help asphaltene disperse in crude oil. These materials coexist in equilibrium until petroleum cracking occurs, at which point they separate and create spaces inside the asphaltene layers as a result of the removal of resin.

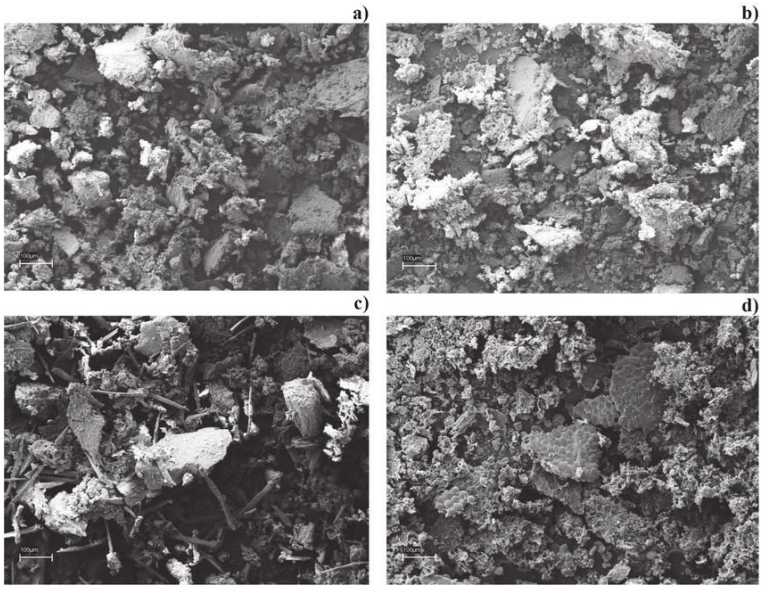


Figure 5. SEM of WCO

3. Experimental plan

Five types of asphalt mix Performance were assessed through conducting Marshall, rutting resistance, moisture damage, and low temperature stability tests. Figure 6 illustrate all stages in experimental design.

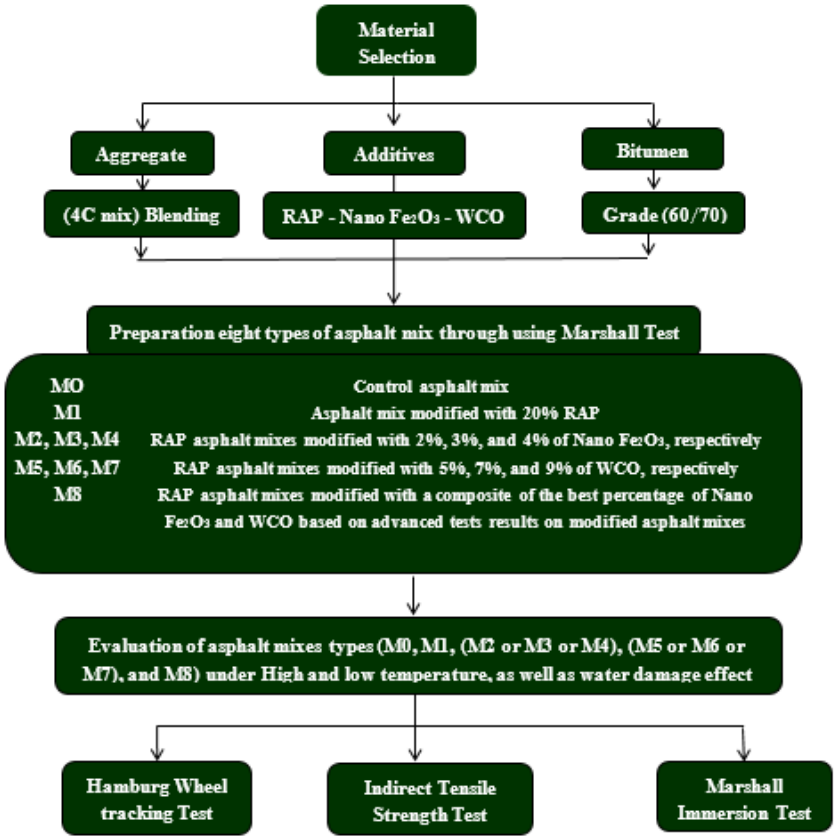


Figure 6. Presented all stages in experimental design

3.1. Specimens Preparation

The dry and the wet method are the two most commonly applied methods for combining additives in asphalt mixes. The dry method is widely applied to additives since it is the simplest to use and achieves better distribution of additives in the mix; it is also often applied in fieldwork. For this analysis, the dry method was used. The aggregates were first heated at 1750C for around four hours. The aggregates were then blended for 90 sec in an automatic mixer before additive was inserted and mixed for another 90 sec (for compound mixture, 90 sec for each type of additive, Nano Fe_2O_3 and WCO), after that, the virgin bitumen was added for another 90 sec at a temperature of 160-170 0C to permit for better spreading, and then the filler powder was mixed for another 90 sec.

3.2. Marshall test

With adding Nano Fe_2O_3 and WCO to asphalt mixes, they serve as a composite material with a more complex structure. For the control and adjusted mixtures, the Marshall Stability test is used to measure the Optimum modifier Content for Nano Fe_2O_3 and WCO. In the current study the Nano Fe_2O_3 was added into asphalt mix with various amount by 2%, 3%, and 4% of bitumen amount while, WCO was put into asphalt mix with different quantity by 5%, 7%, and 9% of bitumen amount. The asphalt samples were prepared using the Marshall Compaction unit, which made 75 blows on every side of the specimens. Each group contains three similar samples (each specimen's diameter is 101.6 mm and height is 63.5±1.3 mm) according to ASTM D6927 Standard test [34]. Marshall's criteria are followed when forming samples, as well as the asphalt content for each asphalt type are presents in Table 4. In this research, based on the Marshall test results and the standard specification, the OAC for modified asphalt mixes is listed in Table 4. The optimum asphalt contents were used with a percentage of 5.2% for control asphalt mixes without additives and 4.5% for all other mixes.

Table 4. Asphalt content for modified asphalt mixes

Mix ID	Mixture Type	Bitumen percent
MO	Control asphalt mixes without additives	5.20%
M1	Asphalt mixes modified with 20% RAP	4.50%
M2	RAP asphalt mixes modified with 2% of Nano Fe_2O_3	
M3	RAP asphalt mixes modified with 3% of Nano Fe_2O_3	

M4	RAP asphalt mixes modified with 4% of Nano Fe_2O_3
M5	RAP asphalt mixes modified with 5% of WCO
M6	RAP asphalt mixes modified with 7% of Nano WCO
M7	RAP asphalt mixes modified with 9% of Nano WCO
M8	RAP asphalt mixes modified with a composite of 4% Nano Fe_2O_3 and 9% WCO

3.3. High temperature performance test

The Hamburg wheel loading test applied for evaluating the dynamic stability behavior of different bituminous mixtures. Due to the Marshall Stability test using the optimum content of bitumen, three samples of the square slab are mixed and compacted 24 times with an impact hammer, the dimensions of each sample are 300 mm long, 300 mm wide and 50 mm thickness. The samples are compacted using a roller compactor tool. The samples are put in a temperature chamber of 60 ± 0.5°C for 6 hours before being used. After that, the plates are loaded with a 0.7 MPa tire-wheel pressure of a solid rubber at a speed of 42±1 cycles per minute over a distance of 230±10 mm along one direction. Related to standard requirements, rolling and loading take 60 minutes. The steps of the test are shown in Figure 7. The permanent deformation of an asphalt mix is measured using a dynamic stability predictor, based on AASHTO T 324-22 [35].

3.4. Marshall Immersion test

Marshall Immersion test was conducted to assess the ability of asphalt mixtures to resist the moisture damage. There are two duplicate categories of samples, each with three samples; each sample's diameter is 101.6 mm and height of 63.5±1.3 mm. The first category was spent 30 minutes in water heated to 60 ^{0}C, while the second was spent 24 hours in water heated to 60 ^{0}C. The steps of the test are shown in Figure 8. The AASHTO T283 standard specification is used to assess Marshall Stability [36]. Therefore, MSR was calculated using the equation below:

$$MSR = \frac{MS_2}{MS_1} * 100\% \quad (1)$$

Where: *MSR* stands for the residual stability ratio; MS_2 is the Marshall Stability after 48 hours of immersion in water; MS_1 is the Marshall Stability of the fresh mixture after 30 minutes of immersion in

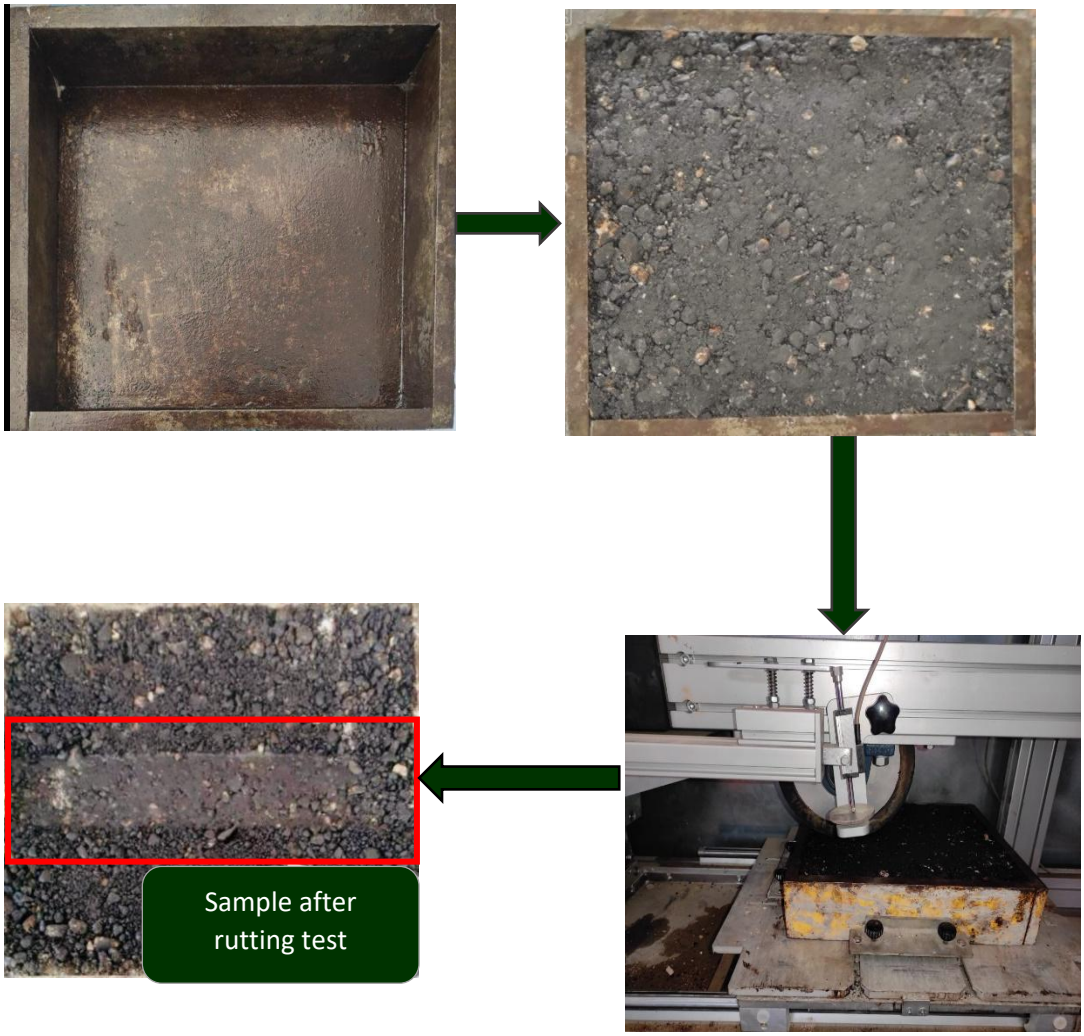


Figure 7. Wheel loading test procedure

water.

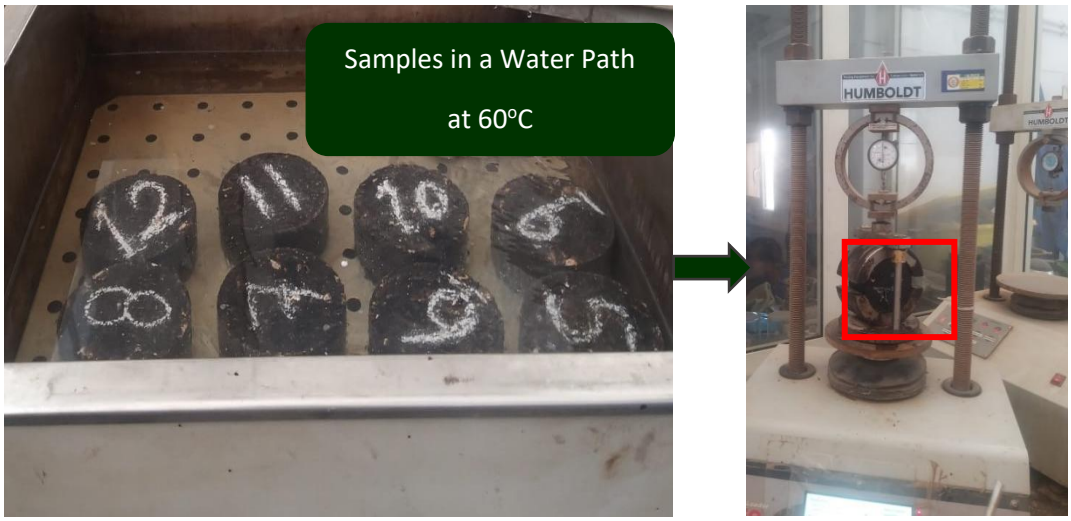


Figure 8. Marshall Immersion test procedure

3.5. Indirect Tensile Strength test (ITS test)

The ITS test was used to evaluate the performance of asphalt mixtures at low temperature. The steps of the test are shown in Figure 9. Three similar cylindrical samples, each with a diameter of 101.6 mm and height of 63.5 mm were prepared. The samples were placed in a chamber with constant temperature for two hours prior to testing at -5°C. Finally, the samples was fixed in the test apparatus and exposed to loading along their vertical diameter with a speed of 1 mm/min, according to ASTM D6931 Standard test [37]. ITS can be calculated based on the following formula:

$$ITS = \frac{2000\,P}{\pi\,d\,h} \qquad (2)$$

Where: ITS is the splitting strength of samples (KPa); P is the indirect tensile loading at failure (N); h is the sample height (mm), d is the sample diameter (mm).



Figure 9. ITS test procedure

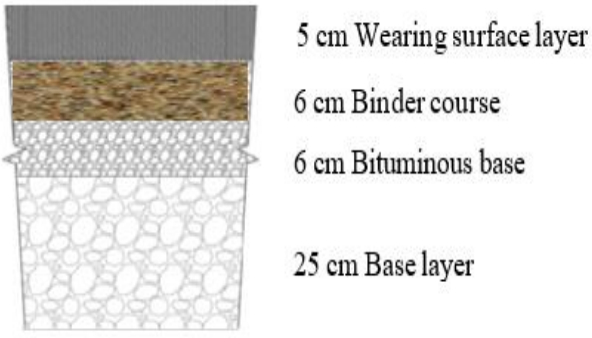
4. Environmental Study

4.1 Purpose of the LCA study

The main purpose of the current study is to calculate, evaluate, and contrast the environmental influences using the LCA method of reclaimed bituminous mixes improved with Nano Fe_2O_3 (and/or) Waste Cooking Oil that were selected for the construction of the wearing surface layer of flexible pavements.

4.2 Function unite (FU)

363 It is the core of any LCA analysis as it is a comparable unit in life cycle inventory. In this study,
364 the functional unit in this research is a part of a standard pavement's wearing surface layer with a length
365 of 1 km and a width of 1 m. The design of the pavement was according to the traditional properties of
366 subgrade support and traffic in Egypt. The geometry, service life, and behavior of bituminous
367 pavements are the most essential factors in establishing the functional unit for road pavement in the
368 LCA technique. The average annual daily traffic used in this research is 20000 vehicle/day with 10%
369 of heavy vehicles at CBR 11%, with design life15 years. The typical cross section is shown in Figure
370 10, based on Marshall design approach [37]. In this analysis, the pavement structure's limitations were
371 restricted to the wearing surface layer. This functional unit is used to calculate all energy consumption,
372 materials, and emissions.



373
374 **Figure 10. Bitumen pavement section used in this research**

375 ## 4.3 System description and boundaries

376 Choosing the system limitations and parameters comprised in the life cycle inventory is very
377 necessary. The system boundaries affect the final outcomes of the research as well as the interpretation
378 of outcomes.

379 The life cycle of pavement construction primarily consists of these phases; design of pavement,
380 production of raw material, transportation, asphalt mix production, pavement building, use,
381 maintenance and the end of life. The aims of this research are to contrast the environmental burdens of
382 the application of modified bituminous mixes. The system boundaries of this study include only these
383 four major processes; production of raw materials, production of bituminous mix, transportation and
384 construction of the pavement. The system boundaries of selected pavement life cycle phases are
385 presented in Figure 11.

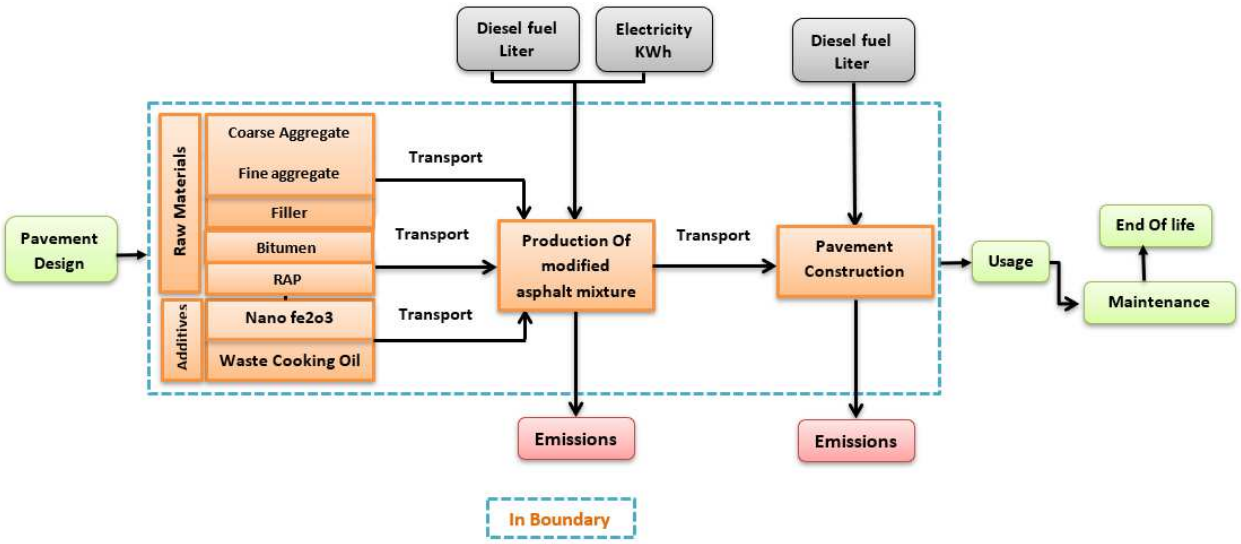


Figure 11. The studied pavement life cycle processes system boundaries

4.4 Data sources and quality

The classification and gathering of data are the most critical processes in the LCA study because they take the greatest time and effort. This study includes a massive number of processes; therefore, enormous quantities of data will be required to perform this study. The quality of data used in this phase of inventory is mainly responsible for the significant results of the LCA. The major sources for life cycle inventories are pilot studies, laboratory tests, databases, and data from literature. In addition, sometimes it is required to make some edits on the data to ascertain the circumstances of a specific boundary of this LCA study. Also, when the suitable data are not available, and to satisfy a qualified inventory analysis, some assumptions should be made.

In the current research, the Ecoinvent database (V 3.6) established by the Swiss Centre for LCI was conducted to estimate the environmental influences of most phases.

Mass balances for the studied bituminous mixtures were measured from laboratory tests and using many data sources, they were modeled with a designed Excel spreadsheet in terms of the density and mix design calculated from laboratory tests for each bituminous mix. Furthermore, the main inventory data was collected through on-site investigations conducted during the construction of a major highway in Egypt, known as the Cairo-Suez Desert Road, which spans approximately 106 kilometers. The lane width of this road is 3.76 meters, with six traffic lanes dedicated to cars and three traffic lanes for heavy transport until it intersects with the regional ring road.

4.5 Assumption and limitation

This research has been applied under these limitations:

- The environmental effects due to only four phases, namely, raw material manufacturing, production of bituminous mix, transportation and construction of wearing surface were included.
- The influences of environment output from the phases of design of pavement, use, and end of life were ignored in this research.
- The raw materials included are limestone aggregates, filler, and bitumen for conventional asphalt mix, whereas nano Fe_2O_3 and waste cooking oil are considered in modified mixes.
- The environmental impacts of the extraction of raw materials, production processes, the pre-chain of diesel fuel production, and the pre-chain of electrical energy production are estimated according to Egyptian conditions.
- The boundaries of the pavement structure were limited to the wearing surface layer. The wearing surface layer construction processes were considered the start point of this study, since other processes of cleaning the site, excavation, compaction of the subgrade layer, in addition to the construction of subbase and base layer were not included because it is shared by all studied asphalt mixtures.
- The environmental consequences of loading materials onto the vehicle were ignored.
- The environmental effects associated with the transportation phase were included for only the one-way trip of materials to the mixing plant of bitumen and bituminous mixes transportation to the pavement construction site, whereas the return trip of empty trucks were neglected.
- Only the environmental implications of bituminous mix production were evaluated, whereas the construction of the bitumen plant, including machinery and electrical installation, were not included.

5. Life cycle inventory (LCI)

During all life cycle phases of the pavement, it outlines the resource consumption and environmental emissions to air, land, and water. The LCA research requires the treatment and measurement of data to provide inventory data for different elements or unit phases. In general, data is gathered from a variety of sources, which may or may not be suitable with the functional unit of present research and must be adjusted to fulfil the study's objectives. This section provides a full explanation of the inventory of the life cycle of the input data used to simulate the studied bituminous mixes of applicable system constituents. The primary mass balances and design parameters of constituents are defined for the bituminous mixes of production procedures. Furthermore, all background operations such as energy and material supply, transportation, resource extraction, and chemical production are gathered and briefly listed from the existing Ecoinvent database (V 3.6). This data is used in SimaPro 9.1.0 software to assess the environmental consequences and burdens for all paving stages. It includes a full explanation of the following inventory data phases.

5.1 Production of Raw Materials Phase

Asphalt mixtures include natural aggregates (gravel, sand, mineral powder), components of the asphalt mastic and additives (Nano Fe_2O_3 and Waste Cooking Oil). Natural aggregates required for the production of bituminous mixes were represented as limestone, and LCI data on their extraction were gotten from the "*Limestone, crushed, washed {RoW}| production | APOS, S*" of the Ecoinvent database unit process. The data of LCI related to the production of bitumen were also obtained from the Ecoinvent database according to "*Bitumen, at refinery/kg/US*". Concerning the production of Nano Fe_2O_3 and Waste Cooking Oil was taken from "*Nano Iron {RoW}| production | APOS, S*", and "*Waste oil, inclusive blowing in {RoW}| production | APOS, S*" respectively, related to the Ecoinvent database.

5.2 Manufacturing of Bituminous Mixes Phase

This phase is purpose to assess the effects of environment due to the manufacturing of the several asphalt mixes considered in this research. The consumption of heavy fuel oil and electricity throughout the manufacturing of the bituminous mix are basically indicated as the major reasons for energy consumption. The building of the machinery that is fixed in the bitumen mixing plant consumes electricity, while the aggregates heating and drying of the asphalt consumes heavy fuel oil. Furthermore,

the aggregates heating and drying of lead to the creation of a lot of dust. In addition, several toxic gases were emitted during bitumen heating. The data of LCI associated with the production of electricity in China, modeled from the database of Ecoinvent related to "Electricity, medium voltage, aluminium industry {CN}| electricity voltage transformation from high to medium voltage, aluminium industry | APOS, S". While the heavy fuel oil manufacturing was also obtained from "Heavy fuel oil {RoW}| heavy fuel oil production, petroleum refinery operation | APOS, S" related to the database of Ecoinvent. Also, as presented in Table 5, the quantity of heavy fuel oil and electricity and desired to produce 1 ton of bituminous mix was gathered from the General Nile Company Plant.

Table 5. Characterization of asphalt mixing plant

Equipment Model	Installation power (Kw)	Rated capacity (T/H)	Capacity of mixer (Kg)	Fuel consumption (kg/t)	Fuel type	Emission Concentration (mg\Nm^3)
SAP100	232	100	1300	≤6.5	Heavy oil	≤20

5.3 Transportation stage

In this stage the transporting process LCI data primarily depends on the type of vehicle and the distance traveled. Fuel consumption and transport phase emissions are measured based on material weight, truck type, transport distance, and categories of roads. All materials and mixtures are assumed to be hauled by a heavy-duty vehicle (HDV). The process "Transport, freight, lorry > 32 metric ton, EURO3 {ROW}| transport, freight, lorry > 32 metric ton, EURO3 | APOS, S" of the Ecoinvent database was utilized to evaluate the environmental impacts linked to the raw materials and asphalt mixture production transportation via highways. The transportation distances for all raw materials and asphalt mixtures used in the current study are displayed in Table 6.

Table 6. Transportation distances considered in this study

Type of material	From	To	One-way trip distance (Km)
Aggregates (Limestone)	Extraction and processing sites	Asphalt plant	160
Filler (Limestone)		Asphalt plant	160
Bitumen	Petrol refinery	Asphalt plant	90
Waste Cooking Oil	Manufacturing site	Asphalt plant	95
Nano Fe2O3		Asphalt plant	90
Asphalt mixture	Asphalt plant	Construction site	60

5.4 Wearing surface construction process

Although there are various phases in road construction, this study solely looks at the wearing surface layer paving process. Furthermore, it was assumed that the paving procedure was the same for all types of bituminous mixes. The emissions released during the spread and compact of the bituminous pavement layers from the combustion of construction machinery have environmental effects during this phase. LCI data on construction equipment such as a heavy vibratory roller and a finisher that are solely utilized in this phase, and the energy spent by such equipment is displayed in Table 7. The consumption of energy during the building of the wearing surface resulted from the diesel fuel consumed by the construction machinery. By introducing in the data of LCI, the diesel fuel consumption associated with the operation of different kinds of equipment was determined according to the database of the Ecoinvent "*Diesel {RoW}| diesel production, petroleum refinery operation | APOS, S*".

Table 7. The machinery, energy consumption

Machine	Energy Consumption (Liter/1000 m2)	Fuel type
Heavy vibratory roller	20	Diesel
Finisher	40	Diesel

5.5 Mass balances for different asphalt mixtures

The mass balance of different bituminous mixes namely, control, asphalt mix with 20%RAP, RAP asphalt mix modified with Nano Fe2O3, RAP asphalt mix modified with Waste Cooking Oil and composite of RAP asphalt mix modified with Nano Fe2O3&Waste Cooking Oil that were evaluated in this study are calculated as shown in Table 8.

Table 8. The mass balance of different bituminous mixes in this study

		MO	M1	M4	M7	M8
Mass balance (ton)	Asphalt production	146.79	148.68	145.53	143.64	144.90
	Aggregate 1	30.61	24.70	22.89	21.01	19.92
	Aggregate 2	38.96	31.43	29.14	26.75	25.36
	Fine Aggregate 1	23.66	19.08	17.69	16.24	15.40
	Fine Aggregate 2	44.53	35.92	33.30	30.57	28.98
	Filler	1.39	1.12	1.04	0.96	0.91
	Bitumen	7.63	6.69	6.55	6.46	6.52
	RAP	0.000	29.736	29.106	28.728	28.980
	Nano Fe2O3	0.000	0.000	5.821	0.000	5.796
	Waste Cooking Oil	0.000	0.000	0.000	12.928	13.041
Energy consumption in asphalt mix manufacturing	Heavy fuel oil (kg)	769.9	769.9	769.9	769.9	769.9
	Electricity (kWh)	340	344.9	343.93	343.93	343.93
Energy consumption in the wearing surface construction	Diesel fuel (kg)	51	51	51	51	51

6. Life cycle impact assessment

6.1 Selection of LCIA methodology and impact categories

In this analysis, the globally agreed problem-oriented method is used in this analysis to eliminate higher worries about the outcomes, which is based on the methodological LCA guide supplied by CML2001 method. The research's main goal is not to determine the overall risk or actual harm to environment, or the human health associated with the application of pavement construction. However, the main goal is to compare the potential environmental effects of the treatment choices assessed to evaluate the alternative with the least amount of environmental effects. The CML2001 technique is more suited to the goals and scope of this research because it can be used everywhere in the world.

The greatest significant categories are presented in Table 9 and denote the baseline for the LCIA phase. These categories represent the environmental effects of pavement phases and are based on a well- recognized method [19].

Table 9. Impact categories and method of assessment

Impact category	Units	LCIA method
Abiotic depletion (ADP)	kg Sb eq	CML 2001
Acidification (AP)	kg SO_2 eq	CML 2001
Eutrophication (EP)	kg PO_4 eq	CML 2001
Global warming (GWP)	kg CO_2 eq	CML 2001
Ozone depletion (OLD)	kg CFC-11 eq	CML 2001
Human toxicity (HTP)	kg p-DCB	CML 2001
Freshwater aquatic ecotoxicity (FWETP)	kg p-DCB	CML 2001
Marine aquatic ecotoxicity (METP)	kg p-DCB	CML 2001
Terrestrial ecotoxicity (TETP)	kg p-DCB	CML 2001
Photochemical oxidation (POFP)	kg C_2H_4 eq	CML 2001

The eco-toxicity category consists of numerous subcategories (sediments, marine, terrestrial, freshwater, etc.). Only the impacts on terrestrial, marine and freshwater ecosystems were considered, as they are the most related compartment in the studied areas.

6.2 Classification (Assignment of LCI results)

In this process, the quantified and eligible environmental interferences in inventory analysis are merged and allocated into the aforementioned, choosing effect categories.

6.3 Characterization (Calculation of category indicator results)

In this stage, science-based conversion factors are used to transform and combine the LCI results into an illustrative effective indicator for every specified category. The influences of each indicator

category are calculated by multiplying the related interferences of each category by their consistent characterization factors. In general, characterization phases can be described using a simple formula as showed in Eq.3.

$$IR_C = \sum_C CF_{CS} * M_S \quad (3)$$

Where: IR_C is the effect indicator of category C; CF_{CS} is the factor of characterization that attaches interference S for category C; M_S is the size of interference S.

6.4 Normalization

The normalized value of all categories is measured throughout the characterization stage by dividing the result of every category indicated by the used reference value, as shown in Eq. 4.

$$N_C = \frac{IR_C}{R_C} \quad (4)$$

Where: NC is the value of normalization of category indicator C; IRC is the indicator of characterization of category C; RC is the category C reference value.

Large normalization values compared to the total indicate the worst-performing categories, on the other hand, those with small normalization values compared to the total indicate the better-performing categories. The normalized data applied in this research are dependent on the contribution of the world normalized data in 1995. These data are representative of the Egyptian normalized data. The normalized data for the world in 1995 is presented in Table 10.

Table 10. Normalization factor world 2022 (Yue et al., 2022)

Impact category	Reference unit	Normalization factor
Abiotic depletion (ADP)	kg Sb eq/year	1.57E+11
Acidification (AP)	kg SO_2 eq/year	3.35E+11
Eutrophication (EP)	kg PO_4 eq/year	1.32E+11
Global warming (GWP)	kg CO_2 eq/year	4.15E+13
Ozone depletion (OLD)	kg CFC-11 eq/year	6.01E+8
Human toxicity (HTP)	kg p-DCB/year	5.67E+13
Freshwater aquatic ecotoxicity (FWETP)	kg p-DCB/year	1.81E+12
Marine aquatic ecotoxicity (METP)	kg p-DCB/year	1.9E+12
Terrestrial ecotoxicity (TETP)	kg p-DCB/year	1.4E+11
Photochemical oxidation (POFP)	kg C_2H_4 eq/year	9.59E+10

538 ### 6.5 Weighting/Grouping

539 In this study, the panel approach method is a four-step procedure combined with a Multi-Criteria
540 Decision Aid (MCDA) procedure. A panel of Canadian residents assessed seven environmental factors
541 (ecosystem health, human health, resource consumption, duration, scale, distance to target and
542 reversibility) and assigned weights to each. The weighting factors of 10 effect categories were computed
543 based on a four-step procedure: (1) criteria definition, (2) scoring of every effect category according to
544 selected environmental criteria, (3) evaluation of every criterion's importance and (4) criteria
545 aggregation using MCDA approach to establish a final single weighting score for every effect category
546 as presented in Table 11.

547 **Table 11. Weighting factors of Canadian citizens' panel.**

Impact category	Weight %
Abiotic depletion (ADP)	12.9
Acidification (AP)	9.2
Eutrophication (EP)	7.9
Global warming (GWP)	18.2
Ozone depletion (OLD)	13.1
Human toxicity (HTP)	8.5
Freshwater aquatic ecotoxicity (FWETP)	6.6
Marine aquatic ecotoxicity (METP)	6.6
Terrestrial ecotoxicity (TETP)	6.6
Photochemical oxidation (POFP)	6.8

548 ## 5. Results and discussion

549 ### 5.1. Marshall test results

550 Marshall Test was conducted in the current study to select the best dosages of Nano Fe_2O_3 and
551 waste cooking oil in RAP asphalt mix's modifying. Previous studies demonstrated that the usage of
552 RAP (15-25) % as alternative aggregate leads to improvement in asphalt mix's performance, then
553 testing of 20% RAP asphalt mix in Marshall test was necessary to confirm this ratio in other modified
554 mixes. The results of Marshall test for the control, RAP asphalt mixes, Nano Fe_2O_3 and WCO RAP
555 modified asphalt mixtures are presented in table 12. The outcomes of Marshall test for the various types
556 of asphalt mixes performance are summarized in the following section.

557 It is observed that the density value of asphalt mix modified with RAP (M1) decreased because
558 the density of RAP is less than virgin aggregate. While RAP asphalt mix's stability was slightly

improved because RAP can increase the rigidity of the asphalt mix, it approximately has the same flow of control asphalt mix (M0). Although RAP decreased the air voids in asphalt mix due to the presence of asphalt binder inside the RAP which could fill the voids, it still with range of Egyptian specifications (3-5) %. Then, according to Marshall test, modifying of asphalt mix by 20% RAP improved its Marshall parameters.

Adding of Nano Fe_2O_3 to RAP asphalt mix recorded lower density than M1, due to the light weight of Nanoparticles. The usage of Nano Fe_2O_3 by 2%, 3%, and 4% significantly superior the asphalt mixes stability by 42.88%, 48.68%, and 63.8 % respectively, due to the high thermal stability of Nano Fe_2O_3. While, the adding of little amount of Nano Fe_2O_3 to asphalt mix increased the flow results, the flow value was decreased by increasing Nano Fe_2O_3 in asphalt mix; due to that more adding of Nano led to Stiffness increasing of asphalt mix. However, the flow results of Nano Fe_2O_3 modified asphalt mixes (M2, M3 and M4) are still within range. With the increase of Nano Fe_2O_3 amount the void ratio was increased by reason of its bitumen absorption that leads to increasing the gap between aggregate skeleton.

Table 12. Marshall test outcomes for different kind of asphalt mixes

Asphalt Mix ID		Density (gm/cm^3)	Stability (kg)	Flow (mm)	Air Void %
Control	MO	2.33	1355	3.00	4.20
RAP	M1	2.36	1448	3.10	3.40
	M2	2.27	2069	3.75	4.25
Nano Fe_2O_3	M3	2.29	2153	3.50	3.87
	M4	2.31	2372	2.60	3.43
	M5	2.24	2345	3.15	4.85
WCO	M6	2.27	2205.5	3.50	4.28
	M7	2.28	2084.5	3.75	4.03
Egyptian Specification		------	$\geq$ 1300	2-4	3-5

The low density of WCO led to decreasing the density of the asphalt mixes modified with WCO, which recorded the lowest density comparing with RAP asphalt mix. Moreover, the addition of little amount of WCO to asphalt mix superior the stability values, while it was decreased with the increasing of WCO, due to more amount of WCO leads to decreasing in the durability and rigidity of asphalt mix.

Nevertheless, the stability results of WCO modified asphalt mixes are still superior to M1. The addition of WCO by 5%, 7%, and 9% improved the asphalt mixes stability by 61.94%, 52.28%, and 43.9% respectively. The WCO has a significant influence on the flow of the asphalt mix, it increased the flow value of RAP asphalt mix; due to that WCO contains fatty acids and triglycerides that can interact with the bitumen and alter its chemical composition. In addition, it is noted that with the increase of WCO dosage, the void ratio decreases due to the more amount of WCO play a crucial role with virgin bitumen to fill the voids among aggregate skeleton.

Consistent with the requirements of Egyptian specifications, M4 (asphalt mix contains 4.50% bitumen, 20% RAP and 4% Nano Fe_2O_3) and M7 (asphalt mix contains 4.50% bitumen, 20% RAP and 9% WCO) revealed the optimum Marshall characteristics referring to the optimum content of Nano Fe_2O_3 and WCO respectively, among all various ratios of modifiers into asphalt mixes.

7.2. Advanced tests of modified asphalt mixes

7.2.1. Rutting Test

High temperature stability is the ability of asphalt mix to withstand the plastic deformation of bitumen at high temperatures. The wheel loading test was used to estimate the influences of Nano Fe_2O_3 and WCO on the RAP asphalt mix at high temperature (about $60^{O}C$), under repeated concentrated load. Figure 12 shows the rutting depth of control, RAP asphalt mixes and modified RAP asphalt mixes with Nano Fe_2O_3, WCO and couple of them.

Based on the rutting depth of control asphalt mix, it is clear that adding of 20% RAP in asphalt mix in (M1) improved the rutting depth by 15.30%; because of the durability enhancement of asphalt mix resulted from adding RAP. Depending on RAP asphalt mix rutting depth, the double additives of Nano Fe_2O_3 and WCO in (M8) achieved the greatest improvement in RAP asphalt mix's rutting depth; as the rutting depth was decreased by 38.60%. The reason of this improvement goes to the strong cohesion bond between Nano Fe2O3, WCO, bitumen, aggregate and RAP in high temperature, which strengthen the asphalt mix.

The results also documented that the Nano Fe_2O_3 significantly enhanced the rutting resistance in comparison with RAP asphalt mix. Nano Fe_2O_3 in (M4) decreased the rutting depth by 13%. Nano

Fe_2O_3 can enhance the thermal stability of asphalt mix through providing improved thermal resistance. This also can avoid the mixture from softening excessively under high temperatures effect, that is critical for maintaining the structural truthfulness of the pavement. Moreover, the usage of nanoparticles characteristically leads to enhanced stiffness, strength, and the adhesive properties of asphalt to ensure better bonding with aggregate materials. Likewise, Fe_2O_3 can act as an antioxidant, theoretically providing high resistance to oxidative aging. As shown in figure 4 Nano Fe_2O_3 has a larger surface area related to their volume, which can main to upgraded interactions with the bitumen, as well as Nano Fe_2O_3 can affect the viscoelastic properties of the bitumen, which can lead to decrease the viscosity at high temperatures, considering better workability, while still maintaining stability against deformation and flow. All these reasons may lead to reduce rutting, deformation, and deterioration of asphalt under heavy loads over time, and enhanced overall performance of asphalt pavements in the hot areas.

On contrast WCO modifiers slightly increased the rutting depth of RAP asphalt mixes by 10%, which indicated to the insignificant effect of WCO to improve the RAP asphalt mix performance in high temperatures, but adding of RAP and WCO to control asphalt mix could improve the rutting depth by 6.7% comparing to control asphalt mix.

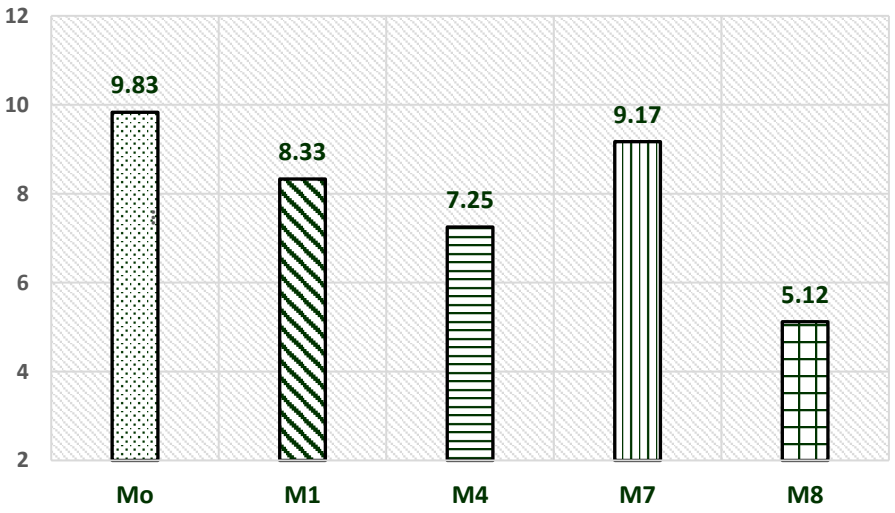


Figure 12. The wheel loading test outcomes

7.2.2. Indirect tensile test result

The indirect tensile test was used to determine the impact of RAP, Nano Fe_2O_3 and WCO on the asphalt mixture's cracking resistance in low temperature; as low temperatures can cause traditional

asphalt to become brittle and break. The indirect tensile strength was calculated according to Equ. 2, and the results are detailed in Figure 13.

Based on control asphalt mix (M0) tensile strength in low temperature, the results revealed that the strength of RAP bituminous mix in (M1) was increased by 10%; because the extra amount of bitumen in RAP leads to air voids elimination and strengthen the cohesion bond between the asphalt mix's components, while adding of Nano Fe_2O_3 to RAP asphalt mix in (M4) showed a little tensile strength improvement by 11.3%. Adding of Nano Fe_2O_3 enhanced the RAP asphalt mix's tensile strength; since asphalt's ductility can be increased and the viscosity decreased of bitumen by nano Fe2O3, which will help it stay flexible at lower temperatures and lessen the chance of cracking. Moreover, the addition of nano Fe_2O_3 to asphalt has the potential to enhance its thermal properties, hence promoting temperature stability and improved performance in cold climates.

The tensile strength of bituminous mix modified with RAP and WCO (M7) was improved by 17.12%; as Waste cooking oil has the power to change the molecular structure of asphalt, making it less brittle and more resilient to stress at low temperature. As well as, adding leftover of WCO in RAP asphalt mix can enhance the asphalt mix's workability by better distribution and compaction of the bitumen, which may result in a pavement that is more consistent and long-lasting, the viscoelastic qualities of aged asphalt binders can be restored by the rejuvenating effects of the long-chain fatty acids in WCO. Furthermore, WCO can increase the adherence of the aggregates to the asphalt binder, enabling a stronger bond with the particles, and increase the bitumen ductility, permitting it to deform more simply under stress without cracking. This is especially crucial in colder climates where moisture can cause bond breakdown and peeling. Some of the fatty acids in WCO have antioxidant qualities that may help to delay the asphalt binder's aging process. The chemical makeup of WCO may contribute ductility and fatigue resistance enhancement to the asphalt mixture, as well as its improved workability by reducing stiffness at low temperatures and lengthening service life.

It's noted that, double additives of Nano Fe_2O_3 and WCO to RAP asphalt mix (M8) recorded the highest resistance to thermal cracking, where the ITS of M8 is superior by 30.21% than M0. The reason

of this result backs to the properties of RAP, Nano Fe_2O_3 and WCO and their combination which affect the tensile strength of asphalt mix positively in low temperature.

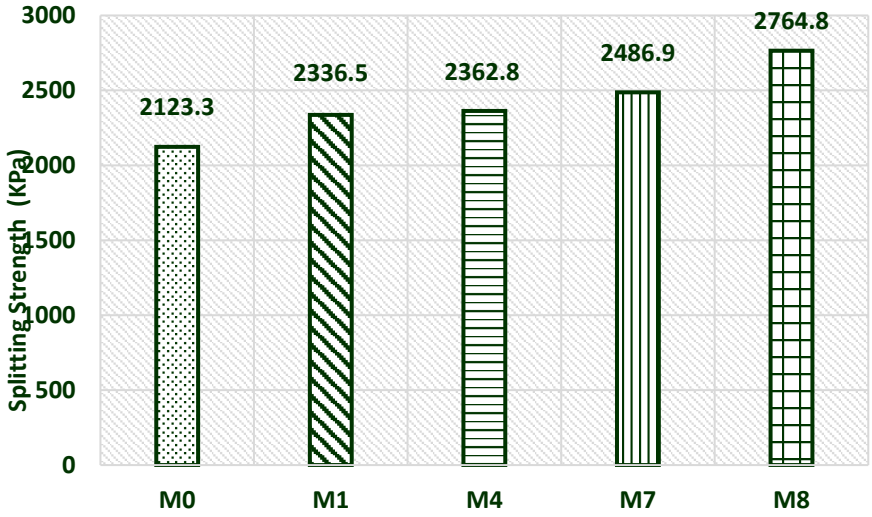


Figure 13. The Indirect Tensile test outcomes

7.2.3. Marshall Immersion test result

The Marshall Immersion test was selected in the present study to assess the moisture damage resistance of the modified asphalt mix. Figures 14 depict the relation between Stability values and MSR with various forms of asphalt mixes. The results denoted that the MSR was enhanced by 4.22%, 7.33%, and 5.07% for asphalt mixtures modified by RAP, Nano Fe2O3, and WCO, respectively, based on the ordinary mixture. On the other hand, it is observed that the composite modified asphalt mixture (M8) documented the highest resistance to water damage with increased about 8.24% than the ordinary mixture (M0).

The results of Marshall Immersion test showed that the asphalt mixtures' water stability behavior had enhanced by asphalt mix modification. Although the RAP asphalt mix (M1) showed higher resistance to moisture damage than (M0), as RAP grants durability to the asphalt mix, adding of Nano Fe_2O_3 in (M4) strengthen the RAP asphalt mix.

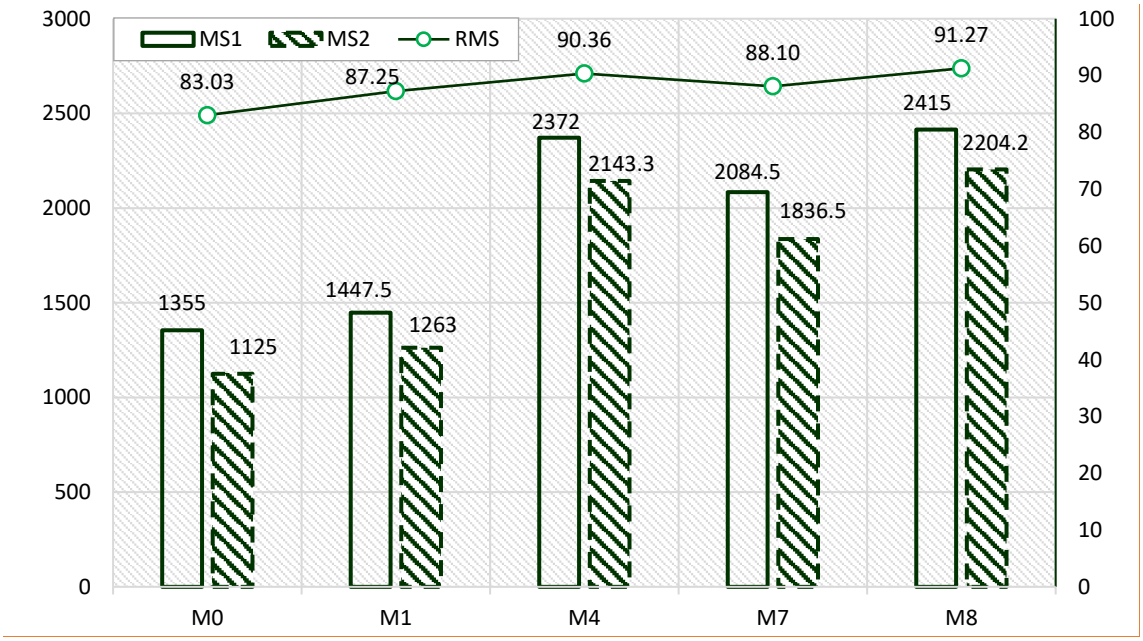


Figure 14. The Marshall Immersion test outcomes

This result back to that Nano Fe_2O_3 particles may affect as a moisture barrier, restricting the mixture's permeability to moisture and humidity by bitumen absorption, which improves the asphalt mix's stability in moist environments. Nano Fe_2O_3 not only improves the asphalt mixture's resistance to water damage but also increases its frictional qualities. In addition, nano play a crucial role in mitigate stripping through enhancing asphalt's hydrophobic qualities, reducing its susceptibility to water absorption, and increase bonding among the aggregates and bitumen.

The effect of WCO in (M7) was less than the effect of Nano Fe_2O_3 in (M4), but it still better than control asphalt mix (M0) and RAP asphalt mix (M1); where WCO can increase the aggregates' adherence to the asphalt binder, making the mixture more resistant to moisture damage. The amount of free bitumen and the spaces between the mix's components are reduced by the oil absorbency. Therefore, by forming a water-repellent barrier, the oily quality of leftover cooking oil can improve the asphalt mixture's resistance to moisture. Furthermore, it might make the asphalt's surface more hydrophobic, which would improve its ability to endure temperature changes and lessen cracking while decreasing moisture infiltration and water resistance. All of these benefits would improve the asphalt's performance under moisture circumstances.

7.3 Comparison of the characterization results

The overall comparison of the characterization outcomes for studied bituminous mixtures is listed in Figure 15. The results demonstrated that all studied bituminous mixes provide an improvement in most effect categories, but some categories do not offer any improvement. The four modified bituminous mixes have a positive impact in the most effect categories, however some categories have a negative impact with a minimal difference from the control bituminous mix such as the TETP, AP, EP, OLD and GWP impact categories in the RAP asphalt mix modified with Nano Fe2O3&Waste Cooking Oil (M8) and the TETP, EP, OLD and GWP impact categories in the RAP asphalt mix modified with Waste Cooking Oil (M7) and the TETP, EP, OLD and GWP impact categories in the RAP asphalt mix modified with Nano Fe_2O_3 (M4) and the OLD impact category in the asphalt mix modified with 20%RAP (M1). Moreover, the RAP asphalt mix modified with Nano Fe2O3&Waste Cooking Oil (M8) has the greatest negative impact in all categories except in the MAETP, FWETP, POFP, HTP and ADP categories, where the four modified bituminous mixes have a positive impact in ADP, HTP, FWETP, MAETP and POFP categories. However, the results also showed that the different asphalt mixtures have the greatest positive impact on MAETP category and have the greatest negative impact on OLD category.

Results demonstrated that the ADP value for M1, M4, M7, and M8 decreased by 11.9, 12.1, 9.1 and 6.8% respectively, when compared to the M0, with the composite mixture (M8) exhibiting the least improvement, as it has the highest ADP value. In addition, the AP value of the M1, M4, and M7 decreased by 9.0, 4.6, and 3.6% and the AP value of the M8 increased by 2.9% respectively with respect to the M0, furthermore, the composite mixture displays the worst results and has negative environmental impacts. Whereas the EP value decreased with the addition of 20%RAP compared to M0 by 5.4%. Moreover, the M4, M7, and M8 increased the EP value by 7.6, 37.7 and 52.5%, respectively. Moreover, the GWP value increased by 1.7, 23.1 and 30.2% for asphalt mixtures modified by Nano Fe2O3, Waste Cooking Oil, and composite Nano Fe2O3&Waste Cooking Oil respectively and decreased by 3.7% for asphalt mixtures modified by 20%RAP when compared to the M0, with the M8 exhibiting the worst results, as it has the highest GWP value. The OLD value of the mixture of M1, M4, M7, and M8 increased by 2.7, 15.1, 35.8 and 48.8% respectively with respect to M0, and the composite asphalt

mixture displays the worst results and has negative environmental impacts. It was observed that the HTP value for asphalt mixtures modified by 20%RAP, Nano Fe2O3, Waste Cooking Oil, and composite Nano Fe2O3&Waste Cooking Oil decreased by 11.3, 10.6, 8.1 and 5.0% respectively when compared to the control, with the M8 demonstrating the least improvement. Furthermore, the FWETP value decreased by 11, 9.7, 6.8 and 3.1% for mixtures of M1, M4, M7, and M8 respectively when compared to the M0. The asphalt mixture modified with 20%RAP displayed the best results, having the lowest FWETP value. Moreover, the MAETP value decreased with the addition of 20%RAP, Nano Fe_2O_3 and Waste Cooking Oil compared to control by 11.9 and 12.4, 11.6%, respectively. Moreover, the M8 decreased the MAETP value by 9.6%. In addition, the TETP value of the mixture of M1 decreased by 1% with respect to M0 and the mixture of M4, M7, and M8 increased by 16.4, 47.7 and 66.1% respectively with respect to M0. The composite asphalt mixture displayed the worst results, having negative environmental impacts. Also, it was observed that the POFP value decreased with the addition of 20%RAP and Nano Fe_2O_3 compared to M0 by 10.2, and 9.1%, respectively. Moreover, the addition of M7, and M8 decreased the POFP value by 5.5, 2% compared to control (M0).

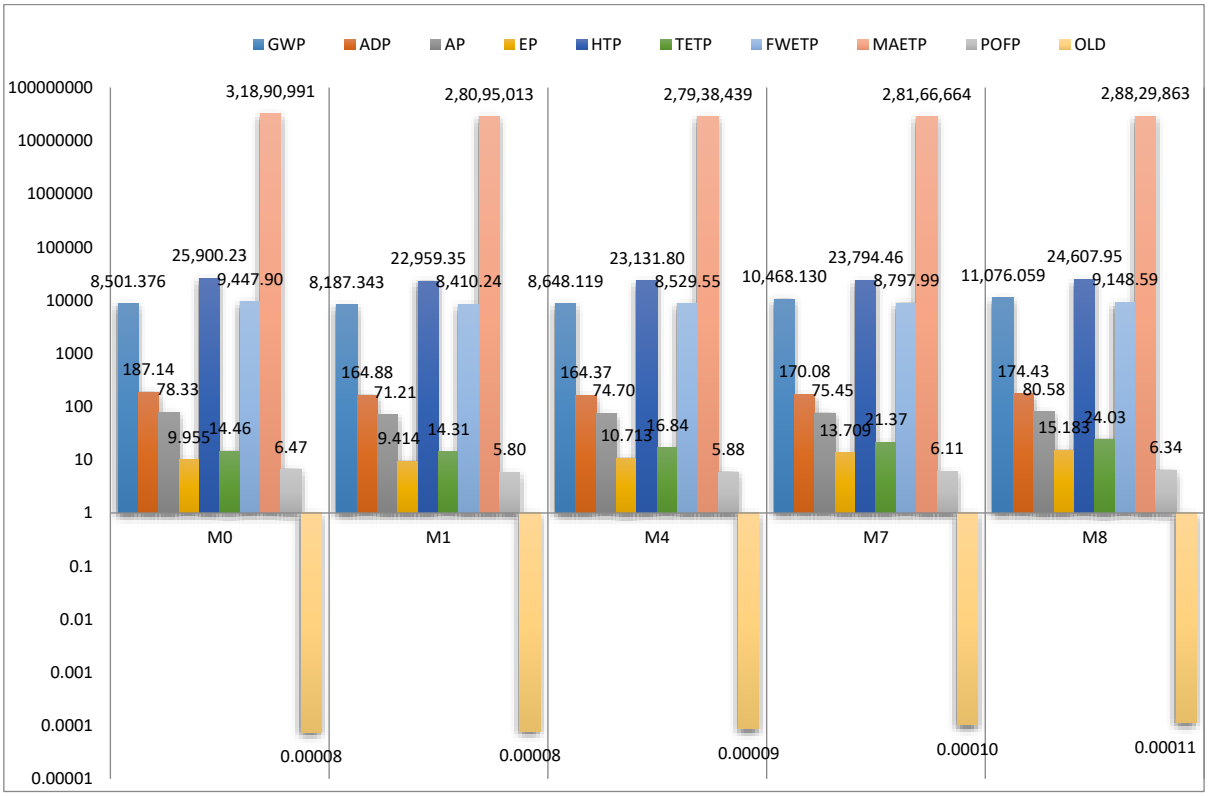


Figure 15. Characterization results of all asphalt mixtures

Figure 16, presents the relative variation of the collective characterization outcomes of all studied modified bituminous mixes concerning compared to control bituminous mix. The negative relative number indicates bad LCIA outcomes on the studied bituminous mixes concerning those related to the control bituminous mix.

The outcomes demonstrated that the environmental effect of the TETP in the Waste Cooking Oil, and composite Nano Fe2O3&Waste Cooking Oil mixtures was the lowest with -48%, and -66%, respectively, followed by the EP impact with -52.5% in the composite mix. It's clear from Figure 8 that the results of all impact categories are obvious and the difference between their values as shown. It can be summarized that the composite mix has the main negative impact in TETP, EP, OLD, GWP and AP categories. While the 20%RAP adjusted bituminous mix has a positive effect in all categories except OLD category as well as Nano Fe_2O_3 adjusted bituminous mix has a maximum positive effect in ADP and MAETP categories but has a negative environmental effect in GWP, EP, TETP and OLD categories.

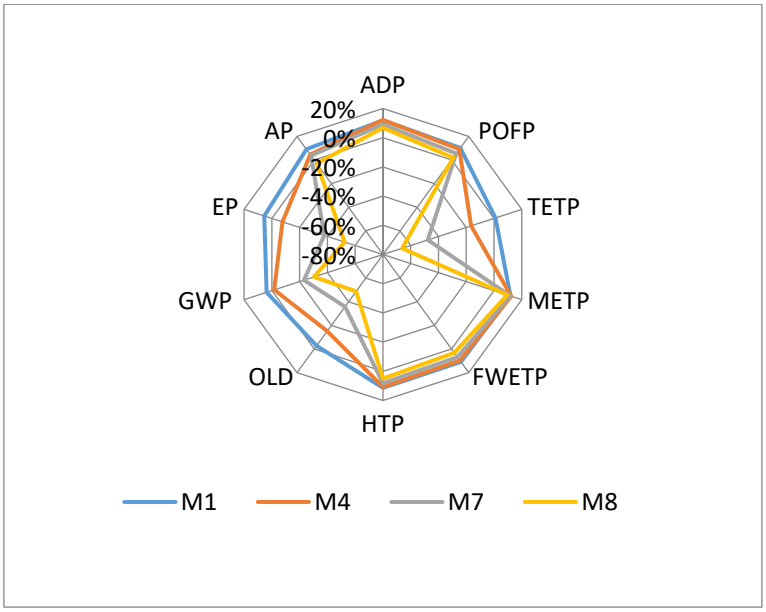
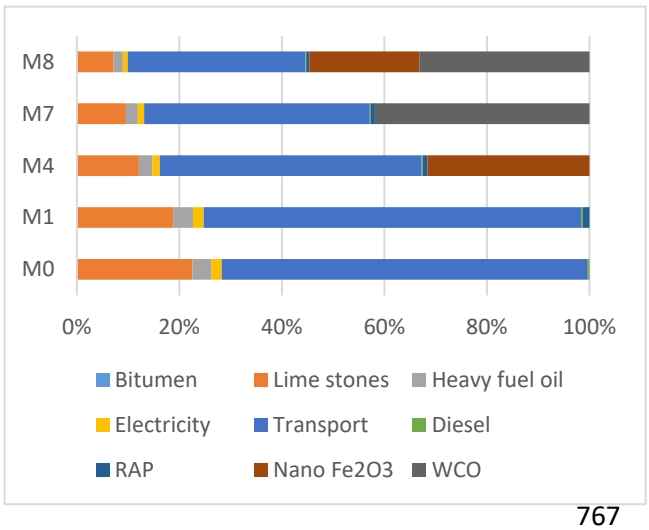


Figure 16. Overview comparisons of all asphalt mixtures

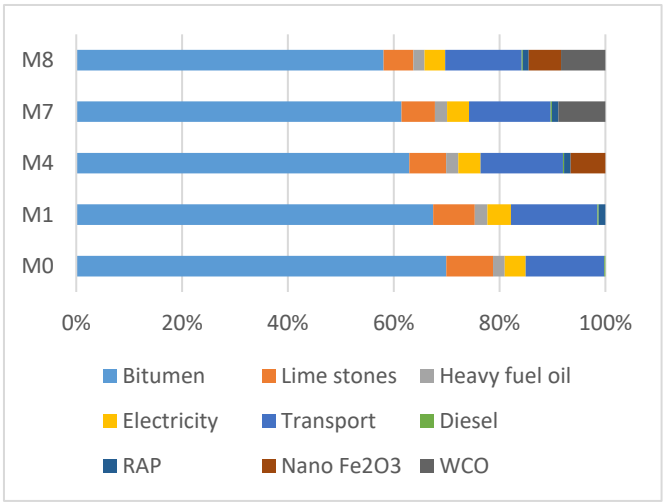
7.4 Process contribution analysis

Figure 17, clarify the contribution of relative phases to the considered environmental categories of the studied bituminous mixes. The analysis results of this figure revealed that the bitumen production, asphalt mixture manufacturing, and transportation, mainly drive the environmental impact profile of the

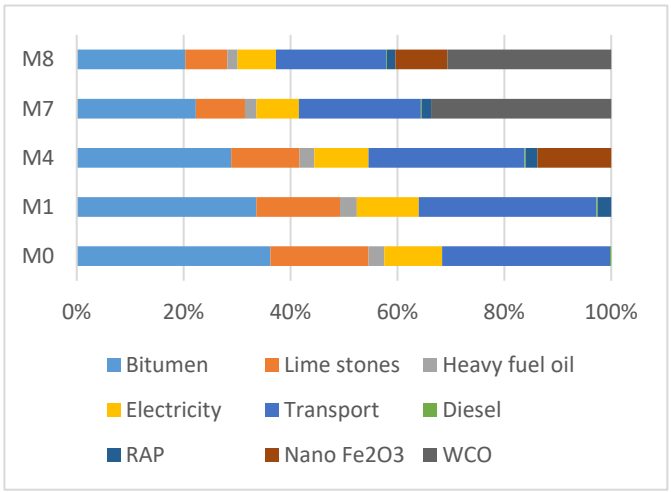
different mixtures, while the variation of impact category is mainly responsible for that exact order. The bitumen production process has the highest contribution for the impact categories AP, EP, GWP, HTP, FWETP, MAETP, and POFP. Furthermore, the asphalt mixture manufacturing process has the highest contribution to the impact category OLD. Finally, the transportation process has the highest contribution to the impact categories ADP and TETP.



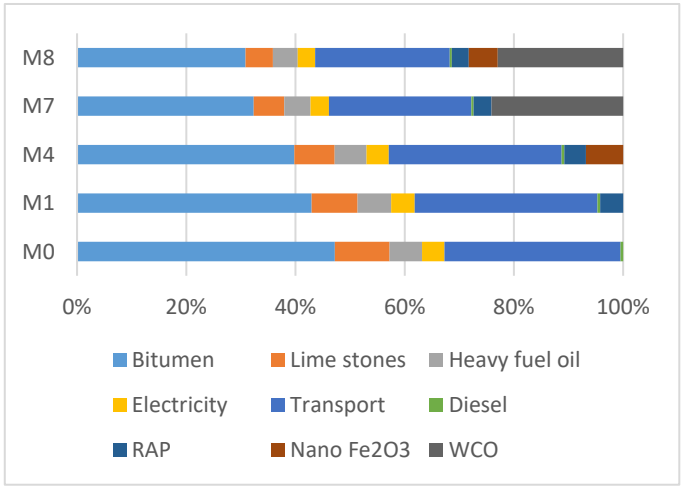
(a)



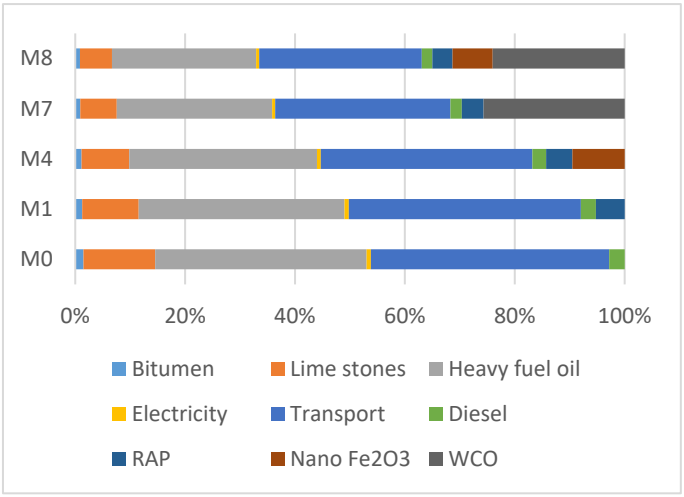
(b)



(c)

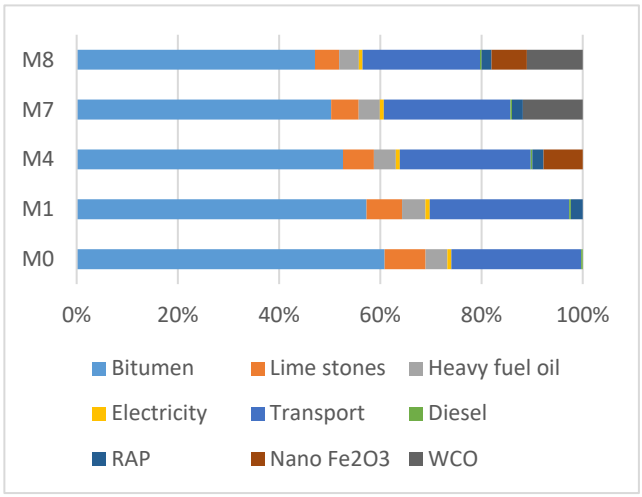


(d)

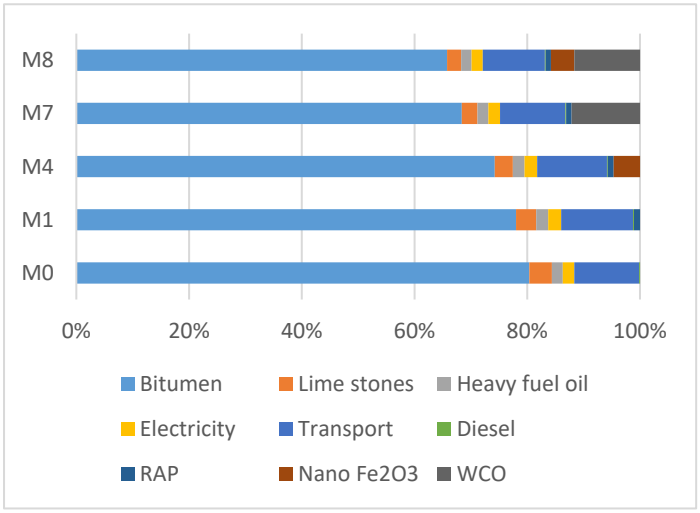


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772 (e)

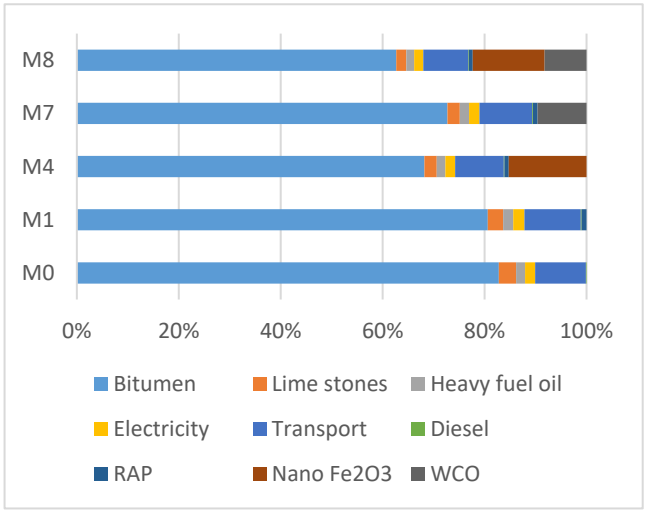


(f)

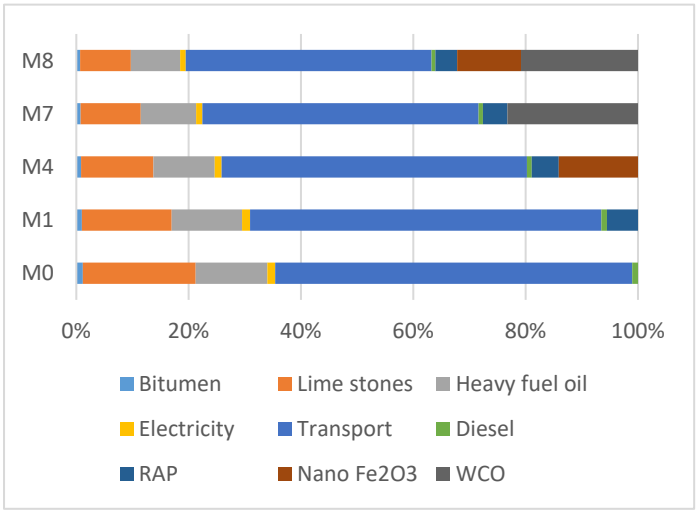


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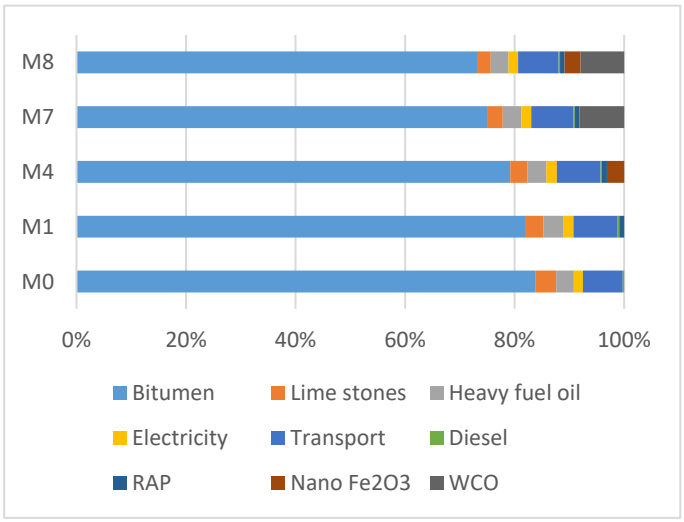
774 (g)



(h)



775 (i)



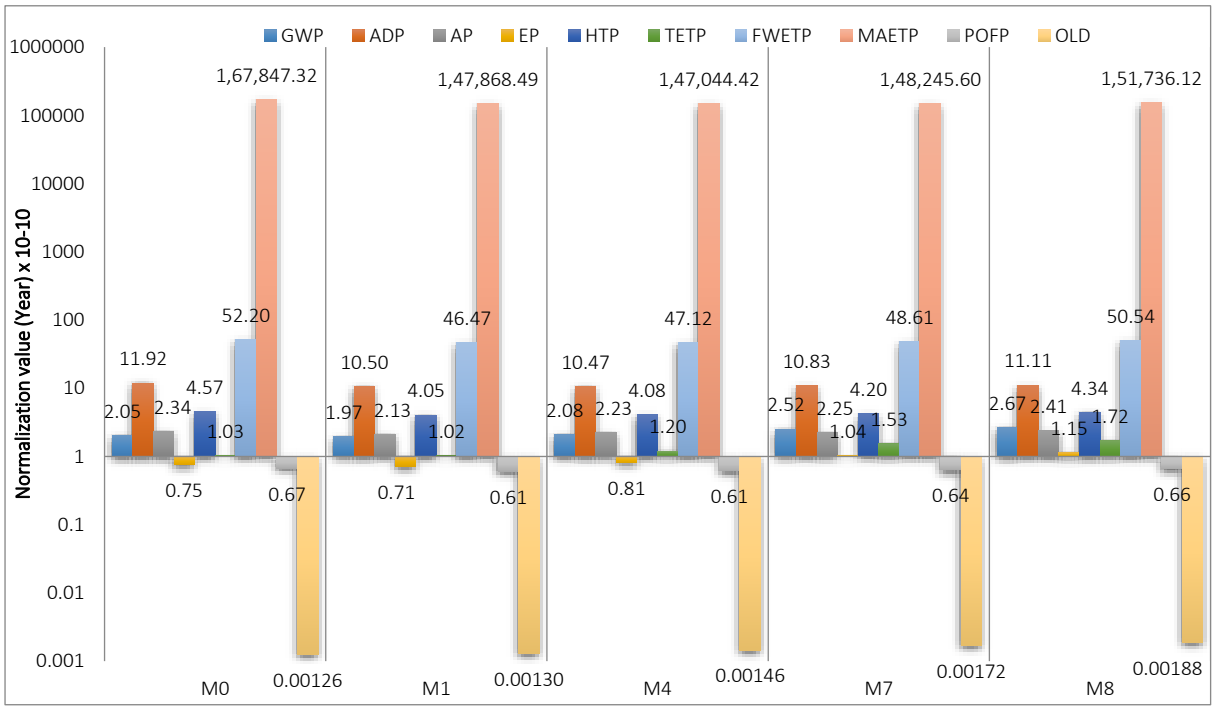
(j)

776 **Figure 17. Relative contribution of the main processes to the total impact scores: (a) ADP, (b) AP, (c) EP,**
777 **(d) GWP, (e) OLD, (f) HTP, (g) FWETP, (h) METP, (i) TETP and (j) POFP.**
778 Acronyms: ADP – Abiotic Depletion Potential; AP – Acidification Potential; EP – Eutrophication Potential; GWP
779 – Global Warming Potential n; OLD – Ozone Layer Depletion; HTP – Human Toxicity Potential; FWETP –
780 Freshwater Ecotoxicity Potential; METP – Marine Ecotoxicity Potential; TETP – Terrestrial Ecotoxicity potential;
781 and POFP – Photochemical Oxidant Formation Potential.

782 ## 7.5 Computation of Normalized Score

783 Figure 18 revealed that the MAETP category is the largest participant in all impact categories of
784 the reference community, therefore it is considered the worst impact category compared to other
785 categories followed by FWETP, ADP and HTP. The figure also proved that different asphalt mixtures
786 achieve well in four groups: OLD, POFP, EP and TETP respectively, as normalization of the
787 characterization indicators, showed a very limited share in these impact categories with comparison to
788 the whole environmental influences of reference community. On the other hand, the AP and GWP
789 categories had a low participation in the environmental impacts. All bituminous mixes have a small
790 difference of normalization in all impact categories.

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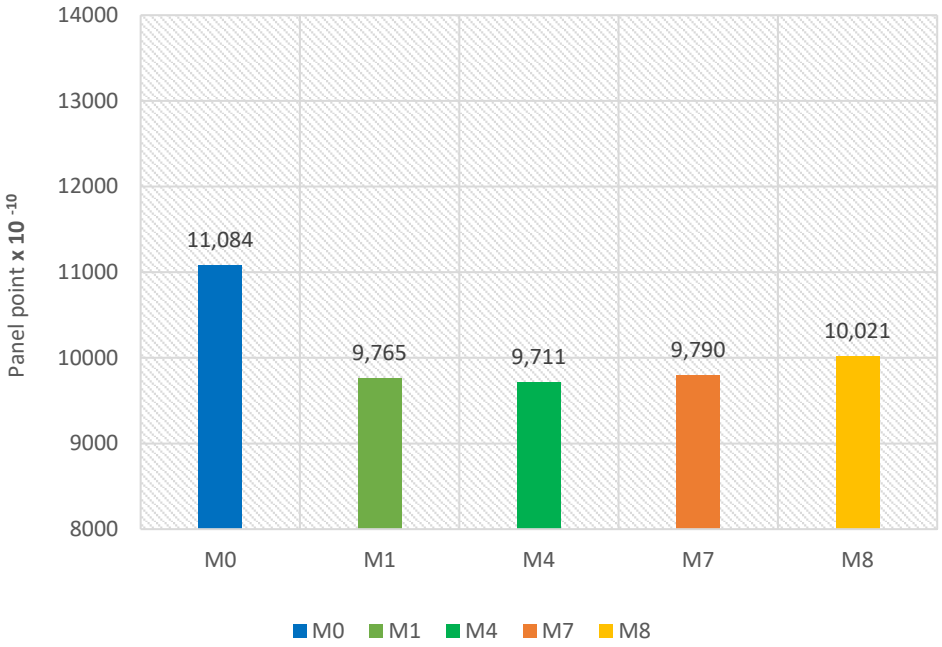


792
793 **Figure 18. Normalization results of the different asphalt mixtures**

794 ## 7.6 Weighting and grouping

795 The results of a panel weighting method (Canadian panel) for the studied bituminous mixes are
796 shown in Figure 19. The outcomes revealed that the weighting score decreased by 11.9, 12.39, 11.67
797 and 9.59% for asphalt mix modified with 20%RAP, Nano Fe2O3, Waste Cooking Oil, and composite

798 Nano Fe2O3&Waste Cooking Oil respectively when compared to the control. The control mixture has
799 the greatest environmental effects of comparing mixes. The RAP asphalt mix modified with Nano
800 Fe2O3&Waste Cooking Oil has the second-highest environmental effects, followed by the RAP asphalt
801 mix modified with Waste Cooking Oil. While the RAP asphalt mix modified with Nano Fe_2O_3 was the
802 best mixture that has the lowest environmental impacts of the comparing mixtures.



803
804 **Figure 19. Weighting profiles of the different asphalt mixtures using the Panel weighting method**

805 ## 8. Conclusions

806 The moisture damage, low and high temperature stability of RAP asphalt mixes modified with the
807 single or double additive of Nano Fe_2O_3 and WCO are experimentally assessed. The outcomes showed
808 that adding a single or double additive of Nano Fe_2O_3 and WCO in RAP asphalt mixtures can increase
809 the stability of moisture susceptibility, low and high temperature, therefore affording greater
810 characteristics of RAP asphalt mixes in comparison with to base mix or RAP asphalt mixes without any
811 additives. Moreover, the environmental effectiveness and influence of additives in bituminous mixes
812 related to the LCA method for the manufacture of the wearing surface layer segment of a standard
813 pavement in Egypt were assessed and compared with control bituminous mix. This study examined four
814 modified bituminous mixes: asphalt mix modified with 20%RAP, RAP asphalt mix modified with Nano
815 Fe2O3, RAP asphalt mix modified with Waste Cooking Oil and RAP asphalt mix modified with Nano
816 Fe2O3&Waste Cooking Oil. The LCA of road manufacture process was split into these stages: (1) the

production of raw materials; (2) asphalt mixtures manufacturing; (3) transportation of materials; and (4) wearing surface construction. All of the data of these processes according to the existing database of Ecoinvent (V3.6). To model the environmental characteristics of the different bituminous mixes, the SimaPro 9.1.0 program and CML 2001 approach were used according to ISO 14040 guidelines. The major conclusions can be summarized as follows:

- Among various amount of Nano Fe_2O_3 (i.e. 2%, 3%, and 4%) used in the current study, RAP asphalt mixes modified with 4% of Nano Fe_2O_3 (M4) recorded the best performance related to Marshall test properties. On contrast, RAP asphalt mixes modified with 7% of WCO (M7) documented the best Marshall characteristics in comparison with another dosage of WCO namely (5%, 7%, and 9%) modified RAP asphalt mixture.
- The rutting depth, Marshall residual stability ratio, and indirect tensile failure strength of asphalt mixes were improved by adding Nano Fe_2O_3 and WCO.
- WCO (M7) has a higher impact on thermal cracking resistance than Nano Fe_2O_3 (M4), but its improvement in resistance to rutting and moisture damage is lower than Nano Fe_2O_3.
- Nano Fe_2O_3 has a greater effect on enhancing moisture damage than WCO. Moreover, as opposed to WCO, Nano Fe_2O_3 has a significant impact on improving permanent deformation of RAP asphalt mixes at high temperature.
- The RAP asphalt mix modified with composite admixture (M8) indicated high enhancement in the behavior of water damage, stability of low temperature, and rutting over other mixes.
- The asphalt mix modified with 20% RAP (M1) improve the environmental impact in all categories with compared to all asphalt mixes.
- While the M4 and M7 enhance the environmental profile in compared with M0, however, it appears minor negative effects in the EP, GWP, TETP, and OLD categories.
- Concerning M8 improve the overall environmental impact categories in comparison with M0, excepted some categories TETP, AP, EP, OLD, and GWP, that shows a minimal effect.

- Based on the weighting results from the Panel methods, all modified asphalt mixes display the lowest environmental impacts, making it the most environmentally favorable in comparison with M0.

In summary, it is impossible to enhance all a mixture's properties with a single additive. Thus, the use of composite admixtures in construction of pavement would have a higher effect on improving the overall efficiency and service life of asphalt mixtures than the usage of single admixture. Moreover, when compared to their total environmental effects, the composite asphalt mix and other modified mixes improve the environmental profile with respect to control mixture.

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Compliance with Ethical Standards: This research does not contain any studies with human participants or animals performed by any of the authors.

Conflicts of Interest: The authors declare that they have no conflict of interest.

Data Availability: All data generated or analysed during this study are included in this published article.

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