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REVIEW ARTICLE

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STUDY OF REDUCING THE ENVIRONMENTAL IMPACT OF CO_2 EMISSIONS OF FLEXIBLE PAVEMENT MATERIALS: A CRITICAL REVIEW

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ABSTRACT

The main objective of study is to present a summary to the best practical applications and recent investigation results on how to reduce environmental effect of carbon dioxide emissions CO_2 in flexibly pavement materials, including extraction of virgin materials, heating material, hauling of materials from quarry to the asphalt plant and then to paving place, mix design. Another production techniques for the manufacturing of modified mixes such as warm mix asphalt (WMA), cold mix asphalt (CMA) and reclaimed asphalt pavement (RAP) mixes are included in this summary. Additionally, assessment tools of life cycle involved, economic and environmental effects, and long-term performance of modified mixes have also been highlight ted in this study. Sustainability gains had showed this study involved a reduction of fuel use, reducedCO_2emissions in several stage of HMA production, and possible of using RAP and WAM mixes.

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INTRODUCTION

Large quantities of air pollutants are associated with the successive stages of infrastructure, operation and maintenance of highway may significantly variationin airquality (Robinson and Thagesen, 2004). Rapid civilizational developments in all sectors of construction are generally responsible for captain climate change and combined with the main effect of highway transportation on carbon emissions of world wideled to a strong pursuit by governments to develop effective strategies to green highway sector, where the transportation sector is one of the most important sources of carbon emissions in the world, around 20% of worldwide emissions. In French, a carbon emissions reached up to 30%, of which 90% are from highway sector (DE Bortoli, 2015). Pavement production process plays a significant role in contributing to the causes attaching to worldwide warming (Albayati *et al*, 2018). The influence of global warming on the environmental has touched to critical levels. The average global temperature has increased 0.6 ^oC in the previous century and is anticipated to increase from 1.4 to 5.8 ^oC in the next century (Bostanci, 2018). The surface course is the upper outer layer of asphalt highway pavement, it is usually made of dense graded of hot mix asphalt (HMA) (Huang, 2010).

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Asphalt concrete mixture can be characterized as a complex combination that involve of three main parts: aggregate, asphalt binder, and air voids. However, HMA is primarily composed of about 95% aggregates and 5% asphalt binder. (Al-Bayati *et al*, 2018). HMA mixtures blended at high temperatures in order to be capable to dry the aggregate, increase workability and reduce the asphalt viscosity that lead to good coating of aggregate. Production of HMA mixtures at high temperatures needs high energy usage, increase age-asphalt hardening in the mix plant and result in producing of greenhouse gases (GHG)(A. Tutu, A. Tuffour, 2016).Paved surface courses can include up to 45% of an urban area in the United States, these layers are made of either bitumen concrete or Portland concrete cement. Both of these methods contribute to emissions of (GHG) and climate change at both the metropolitan and worldwide scales (Kaloush *et al*. 2010). Carbon dioxide refers to the overall amount of all GHG (generally CO_2) produced indirectly and directly by a certain process, product, or event (Prowell, 2008). According to the process of preparation of bitumen mixtures (a batch mix plant) by which the raw constituents are blended to produce hot mix asphalt (HMA). Firstly, the aggregates are dried, then moved to a blender where it is blended with the bitumen. After blending, the HMA is moved to a storage bin. From the bin, the HMA mixtures are emptied into trucks, which transport the HMA mixtures to the highway project. According to the estimates of the Intergovernmental Panel for Climate Change (IPCC), 13% of overall GHGe missions at the global level are produced yearly from the transportation sector (Sreedhara *et al*, 2016). GHG is measured routinely in terms of carbon dioxide content, although GHG emission comprise many gasses such ascarbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and hydro fluorocarbon (HFC) escape from air conditioning system. Although water vapor is not usually involved, it is the most copious GHG (Brown, 2009). Sources of main emission related to HMA construction are the dryers, bins, and blenders, which emit a variety of gaseous pollutants and particulate matter (PM). In addition, further emission sources are create at HMA plants involve storage silos, where HMA mixtures is temporarily hold; operations of truck load-out, in which trucks carry and transfer HMA mixtures to the project site; storage tanks of liquid asphalt; hot oil heaters (heating the asphalt-storage tanks); and yard emissions (fugitive emissions from the HMA mixtures in truck beds).Combustion of one gallon of fuel releases approximately 22.3 lbs of CO_2(Frederick, 2009).The gaseous emissions emitted from the production process of HMA include the sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOC), as well as volatile HAP organic compounds(Park, NC, 2000).The overall carbon footprint (OCF) for the construction of highways between aggregates material production, bitumen manufacture, site equipment, and transportation can be illustrated in Figure 1.It can be seen that asphalt processing accounts has 44% of the OCF from extraction of bitumen to installation. Naturally, approximately 60 kg of CO_2 are produced per one ton of bitumen produced and laid (Walch *et al*, 2010).

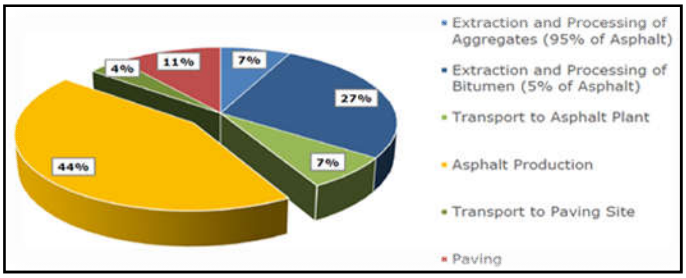

Fig. 1. Example of a pie chart demonstrations overall carbon footprint distribution for a typical highway pavement project (Walch *et al.,* 2010)

These gaseous emissions not only contaminate the air and exacerbate the GHG effect but are also injurious to the health of construction and production personnel. The well-known targets for emission reduction and energy preservation will violate if the current situation continues as it is. For these reasons many current researches have concentrated on decreasing carbon emissions throughout the production of HMA mixtures, including the use of cold mix asphalt (CMA), semi-warm mix asphalt (SWMA) and warm mix asphalt (WMA), (Wang, 2017).At high mixing temperatures is typical temperature of HMA is 140–170°C for a 60/70 asphalt penetration grade, and 150–180°C for a 40/50 asphalt penetration grade (Robinson and Thagesen, 2004).At intermediate mixing temperatures (e.g. WAM), where the range of 80-120 °C. At lower temperatures (e.g. CAM), where the range of 60-70 °C, the asphalt stiffness will be at a certain level so not give sufficient compact ability and workability. (O.R. Larsen *et al*, 2004).The environmental benefits gathered by WMA technologies 10%- 15% smaller carbon footprint related to HMA(Frank *et al*, 2011).The results revealed that the use SWMA mixtures reduced some of emissions at values ranging from 58% for CO_2 to 99.9% for SO_2.One the other hand, CMA production associated with an important reduction in emissions, which offers significant social, environmental and economic benefits. Generally, CMA mixtures are used in highway maintenance and needs a long setting period for good performance and stability of highway (Wang, 2017). The above can be summarized, WMA technology allows the production and paving of WMA mixtures at reduced temperatures produces less emissions and requires fewer energy while the pavement performance will be enhancing gormaintaining (Lou Politano, 2012).Generally, the reduction of emissions from asphalt production is affected by several factors such as the plant condition, climate situations during production and the technology type used (Haopeng Wang *et al*. 2018). Of these reduction methods is the dry process, Waste plastics (WP) can be added to hot aggregates as a coating material by softening the WP and not by burning. Later does not form evolution of gases during burning process like CO_2.For example, a distance of 1 Km single lane asphalt pavement that used WP AS additive need to at least of one ton of WP. A reduction of CO_2 in this accounts may be to 3 tons (S. Rajasekaran, 2013). Another methods to reduce the energy consumption and CO_2 emissions are reclaimed asphalt pavement (RAP).RAP term refers to old flexible pavement broken for again re-use in new HMA mixes, the main function of RAP in the HMA mixtures are to substitute natural aggregates as well as saving virgin asphalt cement since the RAP mixes already coated with aged asphalt cement. The physical and mechanical properties of RAP depend on the RAP source, content of asphalt, and particlesize of aggregates.RAP is an appreciated substitute source with standard engineering properties (Jamshidi *et al*, 2017). According to studies and the investigated on asphalt plants, addition of 30% of RAP mixes into the HMA mixes save about 33% of virgin asphalt cement, where if the asphalt cement percent of new HMA mixtures are 5%, it only requires 3.5% of virgin asphalt cement of the total mixes weight (Ning lee *et al*. 2011). In the past, evaluation of performance and costs was considered a main factor in choosing the pavement type. Newly, sustainable development may be considered most important factor (Prowell, 2008). Sustainability encompass three components are society, economy, and environment. A modern construction systems are often necessary to assess structure projects against the environmental, economic and social of sustainable development requirements (Haifang Wen *et al*. 2014).Modified Asphalt Research Center defined a sustainable pavement as following a pavement that decreases environmental effects through the decline of raw material resources, energy consumption, and related emissions in the same time to meet with standard performance (Haopeng Wang *et al*. 2018).

USE WMA TECHNOLOGY

O.R. Larsen *et al*. (2004) achieved a co-operation investigation between Kolo Veidekke and Shell to develop a method for producing modified asphalt mixture at lower temperatures conditions that have equivalent performances to traditional HMA. They used the foamed asphalt in the warm mix asphalt method (WMA Foam). WMA Foam is a new process, it is produced by combining of a foamed hard asphalt grade with a soft asphalt grade in order to attain a decreasing in operating temperatures (100-120°C).In a batch-mixing plant, Foamed asphalt is made by injection of a small quantity of tap water into hot asphalt pipeline (usually 160 °C to 170 °C)just before the asphalt arrives the mixer. An air gun has been fixed to blow the foaming chamber and pipeline clean after every foam-injection, then the water is quickly evaporated and result in creating a very great amount of foam. Results this research can be summarized as following:

- Production of WAM Foam at lower temperatures between 100°C-120 °C lead to energy savings of about 30% and an equal decrease of CO_2 emissions.
- Improve the working environment for both operators of asphalt plant and asphalt workers as a result from decreases in other GHG emissions and in fume exposure.
- In laboratory investigations, the engineering properties of the WAM Foam are equivalent to the HMA mixtures. In the field, rut resistance, surface texture and longitudinal smoothness of WAM Foam sections is identical related to HMA sections.
- The same standard equipment for paving and compaction that use in HMA mixes can be used in WAM Foam mixes.

A recent review which highlighted to reduce the CO_2emission in WMA mixture have conducted by A. Tutu and A. Tuffour (2016). This study include introducing the several experimental researches about an important advantage related to WMA production. One of the studies state that the lower temperature in WMA manufacture can be reduce CO_2emission about 25%. Another research in this study has estimated that the reduction of the production temperatures of HMA mixes by 20˚C could decrease the CO_2 emissions from both the asphalt and fuel used in the HMA production by around 44%.
Lou Politano (2012) presented a study included trials of the ministry of transportation of Ontario's (MTO) to apply the WMA technology on Ontario roads. To estimate the environmental advantages of WMA, the emissions quantities and temperature measured at the WMA production plant and pavement locations, and other investigations to calculate WMA performance. MTO accomplished the biggest paving amounts of WMA contract to date in Canada, where a 67,000 tonne of WMA pavement contract on the Queen Elizabeth Way (QEW) in 2011 have paved. This study revealed that GHG emissions is reduced from 4.1 to 5.5 kg $CO_{2equivalent}$ /tone at the WMA production plant, and decreased fuel/energy consumption at the WMA production plant from 20% to 35%. In addition the production of WMA lead to a substantial decrease of asphalt fumes at the pavement location, where asphalt fumes behind the paver decreasing 30% dust, 63% benzene soluble fraction, and 64% opacity. The results also confirmed that combined mixes of WMA and RAP the saves energy and emissions were about 100,500 to 134,000 litres of fuel and l, 274,700 to 368,500 kg $CO_{2\ equivalent}$ of GHG emissions.

Another proof of the possibility of reduction the $CO_2$by using WMA mixes has provided by Frank *et al*, 2011. Three locations were selected to estimateCO_2emissions and compare with HMA control mixes. This study displays the environmental advantages appreciated by WMA technologies, where a reduction percent of carbon footprint range from a 10 to 15 related to HMA mixes. As shows this study that the fuel can be saved about 31%, but theCO_2 decrease was only 14 % on average.

Use Rap Mixes

Another study has been completed by Haifen Wen (2012)to study the influence of using RAP in HMA on energy consumption and GHG emission through the application of a mathematical model. Various factors have considered such as RAP content in HMA mixes, the discharge temperature of HMA and moisture content in RAP were studied. The results stated that the usage of RAP in HMA reduce energy consumption at any content of RAP, HMA discharge temperature and moisture content. At low content of RAP in HMA, the added of RAP to HM Arises CO_2 emission, while at high content of RAP CO_2 emission is decreases significantly. However, the usage of RAP affects HMA performance. The feasibility of reducing energy consumption and decreasing CO_2 emissions were studied by Ning lee *et al*. (2011), where RAP used in pavement production, the Life-cycle pavement of assessment tool aimed at economic and environmental effects (PaLATE)" is used to count the pollutants emissions of asphalt concrete manufacture and energy consumption statistics, where Interrelated data of five HMA plants were examined for the analysis. The environmental advantages of using RAP in terms the energy depletion and CO_2 emissions of asphalt concrete mixtures comprising RAP with HMA mixtures. The production process of HMA mixes with RAP are like to that of virgin HMA mixes with entirely virgin materials. But, RAP mix dried at the temperature around 135℃ because the RAP mix contains aged asphalt, and natural aggregates are dried at around 140℃ - 170℃. And then the natural aggregates and the RAP are mixed (dry mix), and then the virgin asphalt cement is sprayed into the RAP and natural aggregates (wet mix). Finally, the production of HMA mixture containing RAP is complete. The replacement percentage of RAP was (0%, 10%, 20, 30%, and 40%) by weight of HMA mixes. PaLATE was advanced by "the Consortium on Green Design and Manufacturing and the Recycled Materials Resource Center". It consist of eighteen Excel worksheets, which can be separated into three groups: Input, Output and Data. Firstly, the operators input the information analysis (material types, material amounts, and equipment) into the input worksheets, and after that results are obtained from the Output worksheets. Basic financial analyses can be also gotten from Palate besides energy depletion and CO_2emissions.According to this research, manufacturing of mixes contains only 30% RAP is needs 84% of energy (16% fuel saving) and emits 80% of CO_2(a smaller amount of 20% emissions) of producing the virgin HMA mixture. At the higher content of the RAP, the higher environmental advantages can be obtained (Frederick, 2009). Introduced the final report include an estimate the effect of using recycling asphalt pavement (RAP) in HMA and recycling concrete aggregate (RCA) in concrete on energy/fuel consumption and GHG emissions. For determine these effects a mathematical model was advanced. The replacement percentages of RAP was 0%, 10%, 20%, 30%,40% and 50% by weight of HMA. Furthermore, other factors such as discharge temperature of HMA and moisture content in RAP were studied. Results indicated to increasing of CO_2 emission at low RAP content (10% RAP), but at high RAP content (50% RAP) the CO_2 emission decreased significantly as illustrated in the Figure (3). CO_2 emission reduction from adding of RAP to HMA is mainly accomplished from the smaller transportation distance for RAP materials. As for fuel consumption, the addition of RAP to HMA saves energy/fuel at any RAP content and moisture content.

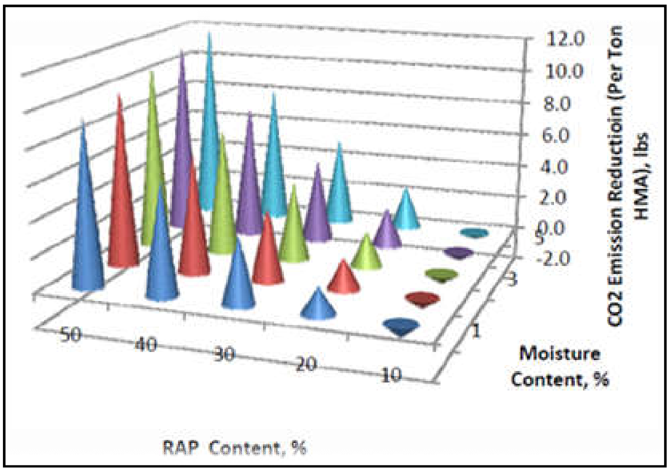

Fig. 3. RAP content with CO_2 Emission, Per Ton of HMA (positive value show that adding RAP to HMA decreases CO_2 emission) (Frederick, 2009)

Use Wma Technlogy and Rap Mixes

Santiago and Osborn (2014) conducted a literature review for modern methods to estimating pollutant emissions throughout asphalt mixes production. In addition, field investigations were complemented to quantity emissions throughout asphalt mixes paving processes, where these of investigation included monitoring of asphalt pollutant emissions to estimate the emission reductions associated with the usage of WMA mixes compared to HMA mixes. Highway pavement project involved four investigation sections, two for HMA mixes and two for WMA mixes, where RAP content is changing, the asphalt concrete comprised 15% RAP for HMA and WMA as well20% RAP for HMA and WMA, the asphalt grade was 67-22.The extensive literature review demonstrate that emission reductions associated with the usage of WMA mixes range up to 40% for CO_2, 30% for CO, 70% for NO_x, 50%for VOCs (volatile organic compounds/blue smoke), and55% for SO_2. As for the field data concluded from placement of WMA mixes and HMA mixes at two different projects, emission reductions were detected range up to 67%. Decreases in Benzene soluble fraction (BSF) reached up to 45% and similarly decreases in Total organic matter (TOM) reached up to 50%. Decreases in polycyclic aromatic compounds (PACs) reached up to 46%.
the variations in GHG emissions and energy / fuel depletion investigated by T. Muench *et al*. (2015) where two types of paving materials in flexible pavement are used, use WMA in place of conventional HMA as well as adding RAP into HMA pavement mixes. The obtained results showed that the use of WMA and RAP mixes in only the surface coarse leads to the reasonable savings of 7,140 $MgCO_2e$ and yearly energy consumption of 657 TJ for HMA mixes in 2010 applications compared to 1990 (supposing 1,000,000 tons per year paved). These values would be decline to 5-15% if the total layers pavement, transportation, and production equipment are considered. Using composed mixes of WMA and RAP can yield larger decreases.

Calculation Model

In relation to the field investigation of the carbon emission (CE) in the road construction, (Peng Bo *et al*. 2017) completed study in which the carbon source was identified in eight stages of bituminous pavement construction (stacking, supply, and drying aggregates, asphalt heating, asphalt-aggregate mixing, asphalt mix transport, asphalt mix paving, and compaction and rolling of mixes. CE were then computed and analyzed of eight stages. Finally the calculation model of CE in the production of asphalt pavement is achieved, the calculation model of CE from coal and heavy weight oil cab be expressed as presented in following formula.

$$GHQ_i = m_i \, .Q_i \sum_{j=1}^{3} GWP_j \, . \, EF_j$$

where GHQ_i is the GHG from coal or heavy weight oil in thestagei, m_i is the consumption of heavyweight oil or coal in thestagei, Q_i is the calorific worth of heavyweight oil or coal in thestagei,EF_j is the emission factor established on the calorific worth of heavyweight oil or coal in the stage I, and GWP_j is theglobal heating potential (used to describe the intensity of relative radiation of GHG) in thestage i. The calculation model of the CE of natural gas cab be expressed as presented in following formula.

$$GHQ_i = v_i \, .Q_i \sum_{j=1}^{3} GWP_j \, . \, EF_j$$

where GHQ_i is the CE of natural gas in the stage i, V_i is the consumption of the natural gas in the stage i, Q_i is the calorific worth of natural gas unit in the i stage, and EF_j is the CE factor established on the calorific worth of natural gas in the stage i. In this research, the kind of energy used in warming process of raw materials is a significant reason affecting CE of as phaltpavement production. In addition, the use natural gas as warming energy would be reduced CE in the pavement production, where CE reduced approximately 32% by applying the strategy of change as phalt warming energy and the aggregate.

CHANGER Software to compare the carbon footprint between HMA and WMA were conducted by SwaroopaKar *et al*, 2015, “CHANGER was developed by the International Road Federation (IRF) and the first version was released in November 2009”. The objective of CHANGER is multifaceted such as simplify an environmental investigation of highway projects, provide the comparative study of many highway laying materials and techniques, estimate the carbon footprint of highway production activities. A four lane highway was as case study, with a width of 3.5 m and with of 62 km at NH 62, Jodhpur Pali Road for both HMA Mix and WMA Mix. The entire paved area was 1,798,000 m^2. The collected data investigated through CHANGER, the results indicated that the CHANGER is a very good tool to assess GHG emission resulting of highway pavement construction, and also stated that the use of WMA technology reduces GHG emissions in terms of equivalent to CO_2 by 32 gm / m^2 paved area, where the reduction of CO_2 emissions for total project was 590 tonne related to 1,798,000 m^2paved area. Kaloush *et al.* (2010) presented a set of recent reference efforts to improve an assessment tool to estimate CO_2 emissions of pavement production and construction. This tool assist the highway designers and transport officials to prototypical the influence of production and construction of different pavements on climate change. Figure 4 illustrations the main components required to model the annual equivalent CO_2 per length of highway section. The annual equivalent CO_2 formula can be expressed in Equation 1 (Kaloush *et al*, 2010).

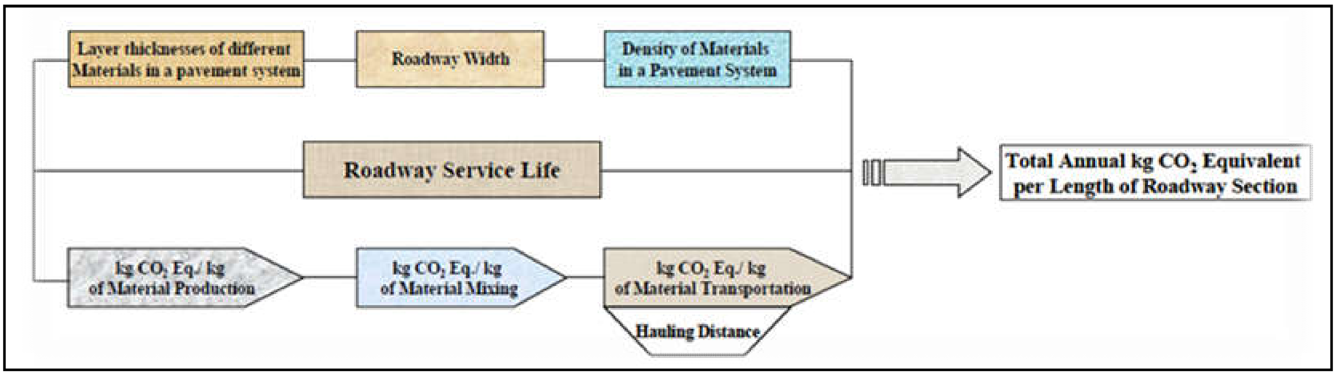

Fig. 4. Components to model the annual equivalent CO_2 per length of highway section (Kaloush *et al*, 2010)

$$Total \cdot annual \cdot kgCO_2 .Eq / km = \frac{\sum [T * W * 1000 * Dn * ((Pn + Mn) + (Di * Tp))]}{Y}$$

Where: T = thickness of layer, meters; W = width of road, meters; D_n = pavement materials density, kg/meters^3; P_n = material production value, kg CO_2equivalent /kg material; M_n= material mixing value, kg CO_2equivalent /kg material; D_i = distance from material production site to application place, kilometers; T_p = transportation from production site to application place value, kg CO_2 equivalent /kg material-km; Y = highway life, years. This study presented a procedure on how pavement production contributes to different climate changes related to the total annual kg CO_2equivalent. The methodology should confirm to be a valuable tool for highway engineers and designers to check the CO_2emissions directly related to the choice of alternative pavement strategies. Operators/users be able to enhance a pavement design depending on organizational requirements in addition to locally climatic conditions, highway maintenance, traffic volumes, and energy requirements.

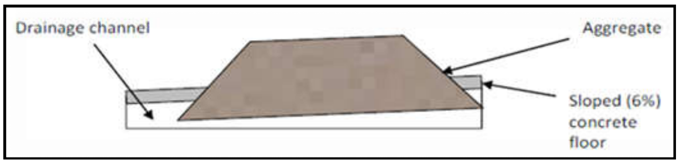

Fig. 1. Aggregate below roof to decrease moisture content (Stotko, 2011)

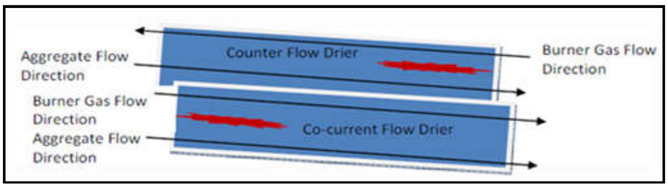

Fig. 2. Drier aggregate/burner gas flow direction measures (Stotko, 2011)

The total possible reductions of carbon dioxideCO_2 from applied measures up to 2 280 tons CO_2/year as well total HFO savings reach to 19 880 GJ/year . These results denote a35% decrease in GHG emissions and a HFO energy saving up to 30%. Chehovits and Galehouse (2010) completed a comparative study on energy usage per unit area and GHG emissions for several process of the production, rehabilitation and preservation of flexible asphalt pavements. Preservation pavements include HMA overlay, hot in place recycling (HIR), chip seal, micro surfacing/slurry seal, crack seal, crack filling and fog seal. Investigation results stated that preservation treatments have considerably reduced fuel/energy usage and GHG emissions related to traditional and reconstruction and rehabilitation strategies. The results divided into three groups. The first group involve the new construction, rehabilitation, thin HMA overlay, and HIR have the maximum annualized values spreading from 3,870 to 12,160 BTU/yd^2-yrfuel energy and 0.9 to 2.4 lb/yd^2- yr of GHG emissions. The second group comprises micro-surface, crack fill, and chip seal at 930 to 2,565 BTU/yd^2-yr fuel energy and 0.13 to 0.35 lb/yd^2-yr of GHG emissions. The final group contains fog sealing and crack sealing with 250 to 870 BTU/yd^2-yr fuel energy and 0.04 to 0.14 lb/yd^2-yr of GHG emissions. The type and amount of materials located per unit area have primary effects on GHG emissions and energy usage for different products.

T. Dorchies 2008 achieved an inventory of fuel consumption and GHG emissions related to highway construction. Investigates include both pavement construction and its maintenance along a service-life of30 years. Different construction types of highway pavement are examined such as HMA, asphalt emulsion technologies, concrete cement pavement, in place pavement recycling (cold pavement), where pavement production process from virgin materials extraction to the service-life of pavement is taken into consideration, these phases involved materials construction, placing of a new pavement, and maintenance workings during its predicted service-life. Inventory results stated that in place pavement recycling using asphalt emulsion as additive is a best method that reduce the GHG effect and energy consumption, where GHG emissions were 5 to 20 kg/t (GHG are expressed in kg of $CO_{2\ eq}$per metric tonne of material). HMA mixes with recycled or without, the GHG was 45 up to 50 kg/t. concrete cement pavement was 140 up to 200 kg/t.

Conclusions

The practical review has stated that RAP and WMA provides important advantages that are compatible with the sustainable pavement concepts. Production process of WMA at temperatures lower 20 ^{O}C from HMA considered a promising technique, all of these studies have shown using WMA decrease CO_2 emissions with percentages from 15 to 40 related to HMA. As for the RAP in HMA, where most investigations illustrated that 50% RAP as replacement percent in HMA mixes reduce CO_2 emissions 10 -20 %.The research has also highlighted to some of the technical procedures for reducing carbon emissions of asphalt plants such as blowing the hot gases in the opposed direction to the aggregate, these results indicate a 35% decrease in GHG emissions. Finally, an assessment tools to evaluate CO_2 emissions of pavement production have presented in this review. This tools help the highway engineers to estimate the influence of production and construction of different pavements on climate change.

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