Systematic literature review, meta-analysis and artificial neural network modelling of plastic waste addition on bitumen

Abstract

Many articles have evaluated the effect of the addition of a wide range of plastic types on bitumen properties. Because each study presents unique characteristics—such as plastic pretreatment, plastic-type, mixing conditions, percentage of addition, and bitumen properties evaluated—it has been difficult for researchers and practitioners to have comprehensive and quantifiable view of the effects. Thus, in the present project, we employed the systematic quantitative literature review (SQLR) to gather, summarise, quantify, and analyse the results of these articles in a practical and replicable manner. It was found that the addition of plastic waste reduces the penetration and increases the softening point and viscosity of bitumen. This behaviour is reported in most of the reviewed literature, regardless of the plastic type, percentage of addition, pretreatment methods, and experimental parameters employed. We employed Bayesian Regularized Artificial Neural Network to develop predictive models to predict the effect of plastic addition and mixing condition on the modified bitumen's penetration, softening point and viscosity properties**.** The models had excellent prediction ability and can help engineers optimise the plastic modified bitumen properties. Furthermore, we reviewed the effect of plastic addition on the bitumen's Superpave properties and found that the majority of the studies showed improvement on the bitumen resistance to hot temperature, but only a small percentage exhibited an enhancement in the cold cracking resistance. Among the drawbacks, the addition of plastic waste tends to deteriorate the workability of the bitumen by increasing its viscosity and by provoking a phase separation behaviour. This study also compiled a summary graph showing the recommended percentages of the different plastic types to be added to bitumen based on the reviewed literature. An addition of 4.5% plastic waste over bitumen weight seems to be the most effective. In conclusion, it is recommended to use plastic waste in bitumens that are intended to be implemented at moderate and hot climates. However, the addition should be limited to less than 5%, so it does not deteriorate the workability of the bitumen.

Keywords

Plastic waste, Bitumen, Asphalt, Systematic quantitative literature review, Metadata analysis, artificial neural networks.

1. Introduction

Bitumen, also known as asphalt, is widely used in road construction because of its waterproofing and viscoelastic properties(Hunter et al., 2015). Bitumen is extracted from the heaviest fraction of crude oil and, although it has a complex chemical structure, its components are usually characterised under four general chemical groups: saturates, aromatics, resins, and asphaltenes (SARA). It is used as the binder component in the construction of flexible pavement. Compared with rigid pavement, flexible pavement has a lower sensitivity to ravelling and is easier to maintain and upgrade. In general terms, the properties most desired in bitumen are resistance to rutting and cracking, good durability and low-temperature resistance(Thom and Knovel, 2013).

Sometimes, natural bitumen does not comply with specific requirements, so it is necessary to add other elements to improve its properties. These additives could be polymers, chemicals, or rubbers. After the bitumen has been modified with these materials, it is usually referred to as a modified bitumen (MB). These additives have demonstrated their capacity to enhance bitumen resistance to rutting deformation, low temperature and fatigue cracking, as well as improved adhesion between the binder and the aggregates(Thom and Knovel, 2013); however, these modifiers have also increased the price of the binder.

As an alternative to the regular polymer modifiers, many researchers have evaluated the use of plastic waste as an additive to bitumen, concluding that this material could be more attractive and economical than the usual polymer modifiers. However, the types of plastics, percentages of plastic waste used, and properties studied vary considerably among studies. As such, it has been difficult to convey all the information contained in the literature into valuable insights for its industrial application and future research into the topic.

Numerous studies that reviewed the use of plastic waste in road construction exist, but they rarely evaluated specific rheological and physical properties of the plastic modified bitumen. For example, Huang et al. (2007) reviewed those articles that investigated the performance of different types of waste as additives in road construction. Although they included plastic, they were not solely focused on plastics. Furthermore, significant developments in the field have taken place since then; therefore, a new study is needed to update readers with state-of-the-art research in this field. Kalantar, Zahra Niloofar et al. (2012) reviewed studies related to the use of plastic wastes in asphalt mixes. Aziz et al. (2015) updated Kalantar, Z. N. et al. (2012) and expanded it to include different organic materials, including bio-oil, rubber, and waste cooking oil. Both studies offered a qualitative evaluation of the advantages and disadvantages of using certain plastic resins as additives in asphalt mixes. However, no quantitative assessment of the impact of adding plastics as a modifier on the rheological properties was presented. Ahmad et al. (2017) reviewed studies on the use of polyethylene terephthalate (PET) as an additive to asphalt mixes; they also included a limited review of the use of polyethylene (PE) and fibre. They concluded that recycled PET is a suitable additive for flexible pavement mixes because they may improve their stability, stiffness, and viscosity. Nevertheless, their review did not offer insights regarding other types of plastics; furthermore, their evaluations were purely qualitative. Most recently, Mohd Hasan et al. (2019) published an extensive review on the use of waste materials, including plastics, in the construction of roads. However, only qualitative evaluation of the impact of the additive on limited properties (rutting, cracking, moisture resistance, and durability) was included. While most of these previous reviews evaluated the traditional properties of bitumen, there has not been an strong focus on Superpave properties. Furthermore, no quantitative evaluation on the effect of the addition of different plastics (including mixed plastics) on the physical and rheological properties of the MB exists. Therefore, this study attempts to bridge the gap by a) conducting a systematic quantitative review of the use of waste plastics as a bitumen modifier, b) conducting meta-data analysis to quantify the effects on the physical and rheological properties of plastic modified bitumens (PMB) and c) developing machine learning models that can predict accurately the change of bitumen properties after plastic waste addition.

The SQLR is a methodology that systematically collects data and quantifies results, making possible the identification of gaps, generalisations, and emerging trends (Pickering and Byrne, 2013). The major advantages of SQLR over the narrative review, which is the primary methodology used by previous studies of the topic, are that it prevents potential biases and is replicable (Borenstein et al., 2009). We find the SQLR convenient because it considers and revises the quantitative and qualitative data currently available. While the qualitative data, such as plastic-type or pretreatment methods, is useful because it permits the identification of new approaches and trends, the quantitative data determines the effects that these qualitative variables have on bitumen's properties. Thus, by applying SQLR, we expect to identify and understand the parameters that influence the bitumen change after plastic addition and the resultant properties of the modified binder. Two additional benefits of this type of review are that it facilitates the creation of meta-data analysis, and it can be easily updated when new articles are published.

In this review, the main objective is to consolidate and discuss the investigations of the use of plastic waste as a bitumen modifier in a systematic, quantitative way and based on these results, identify the advantages, challenges, and future research directions of the topic. To do so, we evaluated the properties of the resultant bitumen reported by previous articles, and gathered them in terms of three main conventional properties (penetration, softening point, and viscosity at 135°C) and Superpave conditions (rutting, fatigue cracking, and cold cracking resistance). Initially, our principal focus was to understand the impact that each plastic-type and percentage of addition had on the bitumen properties; however, during the initial stages of the review, we realized that other factors were also affecting these results. These factors were experimental design parameters, such as plastic size, shear rate, mixing temperature, and others. For this reason, we also complemented the initial study with a metadata analysis of the impact that these parameters exert on the bitumen's conventional properties and with the formulation of artificial neural network (ANN) models. The preparation of this ANN was based on Kim (2017) and on the theoretical framework of McCulloch and Pitts (1990).

This review provides three significant contributions to stakeholders interested in adding plastic waste to bitumen. First, it serves as a guide by providing further understanding of the effects that plastic-type, percentage of addition, and experimental design (representative operation conditions) brings to the main bitumen properties. Second, because it identifies the gaps and drawbacks of the technique, it provides researchers with useful information about where to aim future studies. Lastly, it serves as a means of reassurance. This means that the present review can suggest to the reader where, how and when the addition of plastic waste is viable and what type of issues should be expected.

2. Methodology

This paper employed the SQLR to review articles published after 2009. In this type of review, the first stage is to identify the keywords, which for this study were plastic waste, biomass, plastic pyrolysis, pyrolysis oil, bitumen, and asphalt. The search was conducted in two of the primary databases related to Science and Engineering: Web of Science and Scopus. Additionally, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (PRISMA) was used (Liberati et al., 2009), shown in Appendix A, for reporting this initial stage.

During the initial search, 11,385 articles were found; after removing the duplicates, 9,897 remained. The next stage was screening. In this stage, all the papers with titles that lacked a reasonable relation to the project or were older than ten years were excluded; this left 1,968 articles in total. Then, the final database was subdivided into pre-determined subjects. The final recognised subjects were pyrolysis oil and road construction, plastics and roads, plastic pyrolysis, plastic and waste, modifying binders or bitumen, and waste and roads. Among these subdivisions, the topics 'plastic and roads', and 'plastic and waste-modifying binders' were selected (165 articles). Last, other articles that were not in English, conference papers and academic theses were excluded. Two final extra classifications were created: plastic waste in asphalt mix, and plastic waste in bitumen – with 78 and 82 articles respectively. The present review evaluated the articles that studied bitumen modified with plastic waste— plastic modified bitumen(PMB)—, 82 articles in total.

The first section of the present article is the study of the PMB conventional properties. These conventional properties were penetration, softening point, and viscosity at 135°C. From the 82 articles, 54 measured the penetration of the PMB, 53 the softening point, and 28 the viscosity at 135°C. Because some articles studied more than one property, the sum of the previous values is not 82. It is important to note that authors have used different methods to measure these properties, and they also have employed various bitumen types. As a result, it was not possible to do a direct analysis of this data. Thus, it was necessary to transform it into a normalised data. Therefore, the percentage change in the penetration and softening point were used instead of their absolute values. For the viscosity, the absolute value was kept, so it was possible to graphically indicate the limit that it needs to comply (3 Pa.s).

To complement the previous analysis, artificial neural network models (ANN) were built to predict the effect of plastic addition and experimental conditions on the percentage change of the penetration, softening point, and viscosity at 135 °C. ANN is a machine learning model that imitates the brain for creating predictive models. In these models, the neurons are referred to nodes and the connection of neurons as connection weights. A graphical representation of a simple ANN is seen in Figure 1, where X represents the inputs, W the corresponding weights for each input, b the bias and Y the output. To calculate Y, the ANN model applies an activation function (ɵ(·)) —which can vary according to the desired output— to the inputs and bias. The mathematical representation of this process is described by equation (1) and (2)(Kim, 2017).

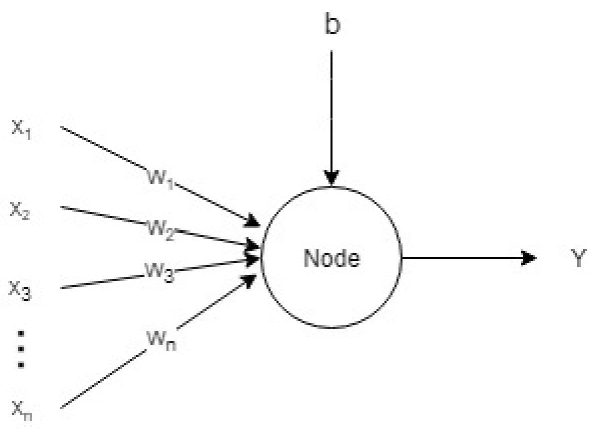


Figure 1 Graphic representation of a node in ANN.

$$v = \left(\sum_{m=1}^{n} x_m W_m\right) + b \quad (1)$$

$$Y = \theta(v) \quad (2)$$

For the formulation of a suitable model, ANN employs a backpropagation process. In this one, an iterative process calculates an error. This error measures how accurate was the model to predict a given data point. With this calculation, the weights are adjusted, so that the error is gradually reduced with each iteration. Some advantages of ANN over other predicting systems are their outstanding learning capacity and their wide application on real-world problems(Chakraverty and Mall, 2017; da Silva et al., 2016).

In the present study, the ANN included multiple neurons, and the input variables were the type of material, the percentage of plastics added, and the experimental conditions. The experimental conditions comprised the mixing temperature, the shear rate, the mixing time and the particle size. The mixing temperature is the temperature at which the bitumen is heated while being mixed with the plastic waste. The shear rate corresponds to the velocity of the mechanical stirrer, and the mixing time is the total blending time. The only property that is not related to the mixing process is the particle size, and this is the size of the plastic waste.

Data collection

The process employed for constructing these models included the data collection stage, data preprocessing, data cleaning, multicollinearity evaluation, ANN model construction, and validation tests. To implement these models, first, we gathered the data from each of the articles reviewed in this study. This collected data were penetration, softening point and viscosity, and experimental parameters. The data were tabulated in an MS Excel™.

Data processing and cleaning

As the collected data came from articles who have used different methods to measure these properties; it was necessary to reshape the data to a more conformant scale. To do so, we used the relative change in the property rather than the absolute value. The relative change is measured as *Relative change=(value after modification – value before modification)/value before modification.* Also, outliers were identified and removed from the dataset by applying the function rmoutliers® in Matlab ™. Data points that are more than three times the Median absolute deviation (MAD) from the Median are considered outliers(MATLAB, 2020b).

As there were some missing data in the records, mainly pertaining to experimental conditions (mixing rate, time, and temperature), it was necessary to use a data imputation method. In this case, we used a multivariate imputation technique that model each feature containing missing values as a function of other features (Pedregosa, 2011a). The function provided by scikit-learn toolbox, sklearn.impute.IterativeImputer® was used to perform this procedure (Pedregosa, 2011b). We then prepared a correlation matrix to evaluate the multicollinearity of the variables and their independency and to gain an overview of the effect of each feature on the observed change in the measured property. There were significant differences in the scale of the variables used. Thus, to avoid scale influence (bias), the data were scaled using the mapminmax® method in Matlab™(MATLAB, 2020d). In this method, the data is scaled in a range between -1 to 1 using the following equation (MATLAB, 2020a): $y = (ymax-ymin)*(x-xmin)/((xmax-xmin) + ymin)$; where, y is the scaled value of feature x; ymax and ymin are the upper and lower bounds of the range (-1 and 1 for this case) and xmax, xmin are the maximum and minimum values of feature x.

ANN model construction

The construction of an ANN model involves the following steps:

1- selection of the architecture
2- train the model
3- optimizing the network
4- testing the model.

Feedforward back propagation networks (FFDBPN) is an efficient and popular ANN fitting architecture for building predictive models. Therefore, it was selected for this study. The next step was to select the backpropagation (BP) algorithm for training. Many BP algorithms may be used depending on the nature of the data. In our case, because the data is collected from different sources

and as such may contain significant noise and because the size of the dataset is relatively small, Bayesian regularization (BR) backpropagation was chosen (MATLAB, 2020c). Another advantage of the BR is that it can present more accurate results than other conventional techniques, such as Levenberg-Marquardt algorithms(Kayri, 2016).
The next step was to train and optimise the network. This is done by selecting the appropriate number of layers and neurons. For this type of problem, a shallow network is deemed appropriate. The network is made up of three layers (input, hidden and output).
Finally, ANN models were constructed using the nftool® provided by Matlab™. The models were evaluated to determine the optimal topology by optimising the number of neurons in the hidden layer. The quality of fit was evaluated by the mean squared error (MSE)(3) and the coefficient of determination (R^2)(4). While MSE represents the sample variance of the errors, R^2 is the variance proportion of the dependent variable that can be explained by the independent variables (Young, 2017).

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(yobs_i - ypred_i)^2 \tag{3}$$

$$R = \sqrt{1 - \frac{\sum_{i=1}^{n}(ypred_i - yobs_i)^2}{\sum_{i=1}^{n}(ypred_i - \bar{y})^2}} \tag{4}$$

where yobs is the data observed (actual data), ypred is the predicted value, and $\bar{y}$ is the mean of the observed values.
For model testing, in addition to the R^2 and MSE, the relative error, the mean absolute relative error (MARE) and the mean absolute percentage error (MAPE) were evaluated. The relative error, MARE, and MAPE calculations are defined in equation (5), (6) and (7), respectively. In these equations, n represents the number of observations.

$$Relative\ error_i(RE) = \left(\frac{yobs_i - ypred_i}{yobs_i}\right) \tag{5}$$

$$MARE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{yobs_i - ypred_i}{yobs_i}\right| \tag{6}$$

$$MAPE = MARE * 100 \tag{7}$$

The second section was the examination of the PMB Superpave properties. The Superpave properties, which is based on the Superpave performance grading (PG), enclose three primary characteristics of bitumen. These characteristics are rutting, fatigue cracking, and cold temperature cracking resistance. The rutting resistance is based on the results of the rutting factor, $G^*/\sin\delta$, which is measured by the dynamic shear rheometer (DSR). The fatigue cracking is based on the fatigue factor ($G^*\sin\delta$) after short time ageing, and last, the cold temperature cracking is evaluated by the outcomes reported from the bending beam rheometer (BBR) testing. Based on the articles' results, and for each Superpave property, we classified the final bitumen into four categories: grading improves; improves but do not comply with the viscosity requirement; no improvement; and grading deterioration.

3. Results and discussion

3.1 Overview

The interest in studying plastic waste as a bitumen additive has increased in recent years, peaking in 2018. Figure 2 shows the number of studies that evaluated the use of plastic as an additive to bitumen per year. The increasing interest of creating alternatives for managing plastic waste, the increase in bitumen prices, and the desire to reduce the environmental impacts of the construction sector may explain this trend(Al-Salem et al., 2017; Zutshi and Creed, 2015). Additionally, another interesting trend is that since 2016 articles have evaluated the usage of plastic waste with a combination of other materials. This new approach means that researchers have already accepted the suitability of plastic waste as a bitumen modifier, and now, they are evaluating other types of materials to further enhance PMB.

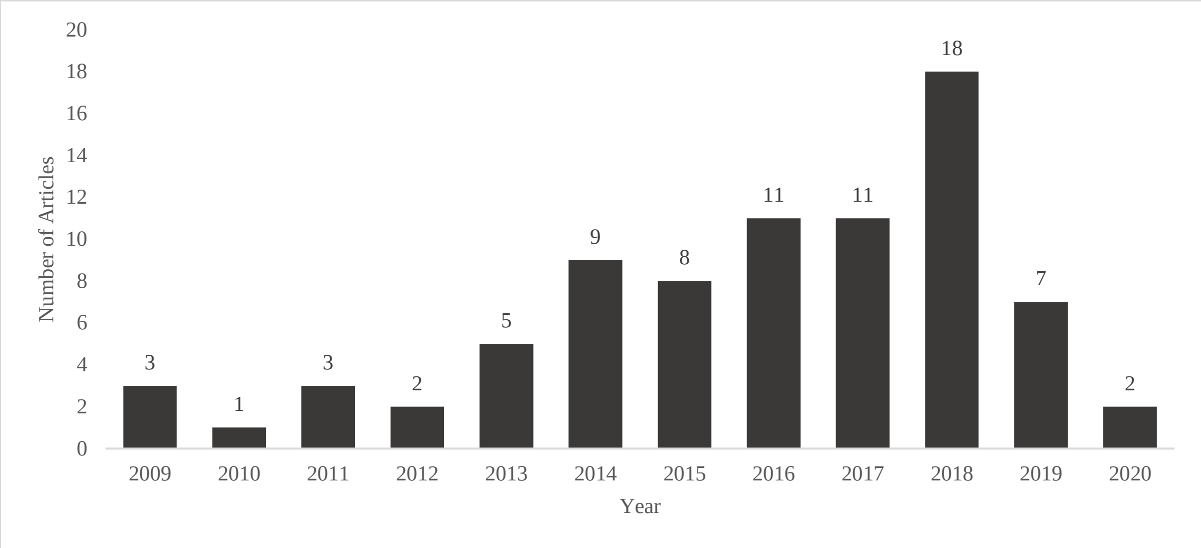


Figure 2 Number of publications per year.

In terms of articles published by country, the most active have been China, India, Turkey, and Iran (Figure 3). China's interest in alternatives for managing plastic waste may be related to the high amount of plastic waste generated and imported in recent years, which has also provoked the development of national initiatives such as the *Green Fence* and stricter restrictions against plastic waste imports. Further, China has the most substantial figures in the world for plastic waste. In 2010, the country generated 59.08 million tonnes of plastic waste, nearly 22% of the total plastic waste generated worldwide, of which 74% was inadequately managed(Jambeck et al., 2015).

India's interest is not only a consequence of its current plastic waste issues, 85% of the total of plastic waste is mismanaged in this nation (Jambeck et al., 2015), but it is also due to the increasing acceptance of this innovative technique in the last years. Notably, Dr Rajagopalan Vasudevan, an Indian scientist with experience in pollution control and plastic waste management, is considered as the pioneer of plastic roads development, since 2002 (Vasudevan et al., 2012; Vasudevan et al., 2010). In one of his articles (Vasudevan et al., 2012), he stated that more than 2500 km of plastic road had been built since 2002, and by 2012 no signs of damage were present. Therefore, this extensive use of the technology and its real implementation might have motivated other Indian researchers to develop this technique further.

Interestingly, some of the countries with the highest rates of plastic waste generation have not studied the usage of plastic in roads as waste treatment, although this might change in the future. According to Jambeck et al. (2015), nearly 50% of the total plastic waste comes from China, the United States, Germany, Brazil, and Japan. Within this group, only China presents high number of PMB scientific publications. On the contrary, researchers in other countries, such as the United States, which generates 14% of the global plastic waste, have not shown interest in studying PMB. In the present review, only two articles came from the United States (Colbert and You, 2012; Liang et al., 2019). In both of these articles, the authors mentioned that one of the motivations for studying this technique was to reduce the waste sent to developing countries, which indicates that developed countries might be starting to be aware of the current plastic crisis and the need for new alternatives to treat it.

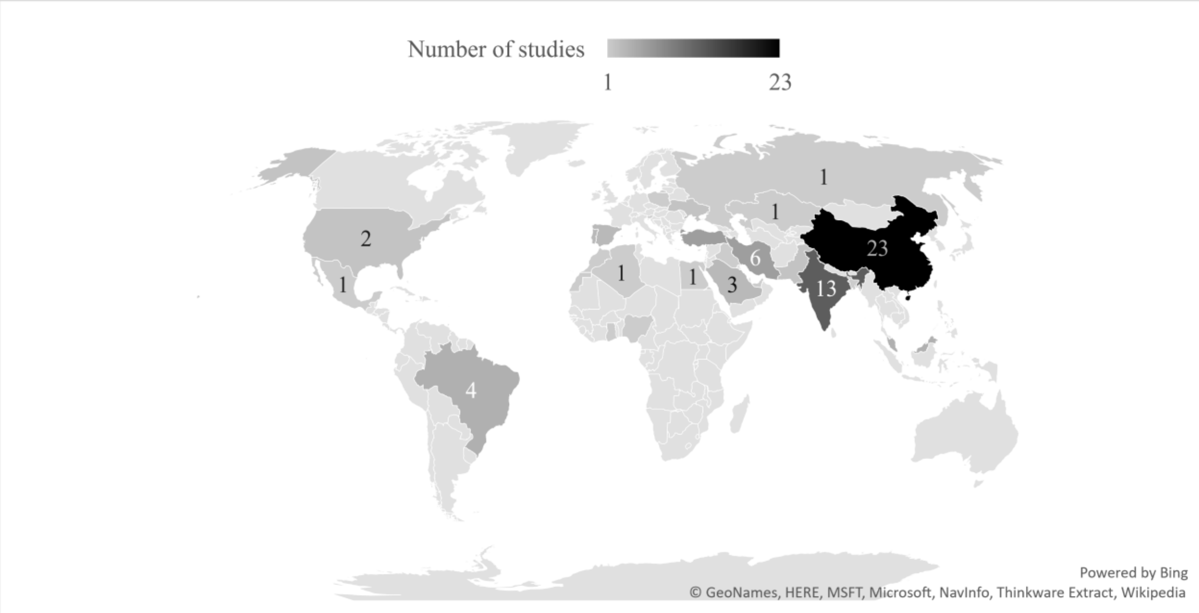


Figure 3 Number of articles per country.

The main objectives in the articles have been to assess the technical feasibility of using plastic waste in bitumen, to evaluate the use of additional material in combination with the plastic, and to evaluate plastic that has been chemically modified (Figure 4). In general, in many of the articles the primary objective was to evaluate PMB performance against raw bitumen. However, in recent years, researchers have also moved to the second stage of the investigation whereby instead of evaluating the PMB suitability, they are trying to improve further this binder. The two significant methodologies to improve PMB has been new pretreatment methods and the addition of another material, which are the common new focus of recent studies. The next section will expand on these pretreatment methods and materials, and describe the common procedures during the mixing process of bitumen and plastic waste.

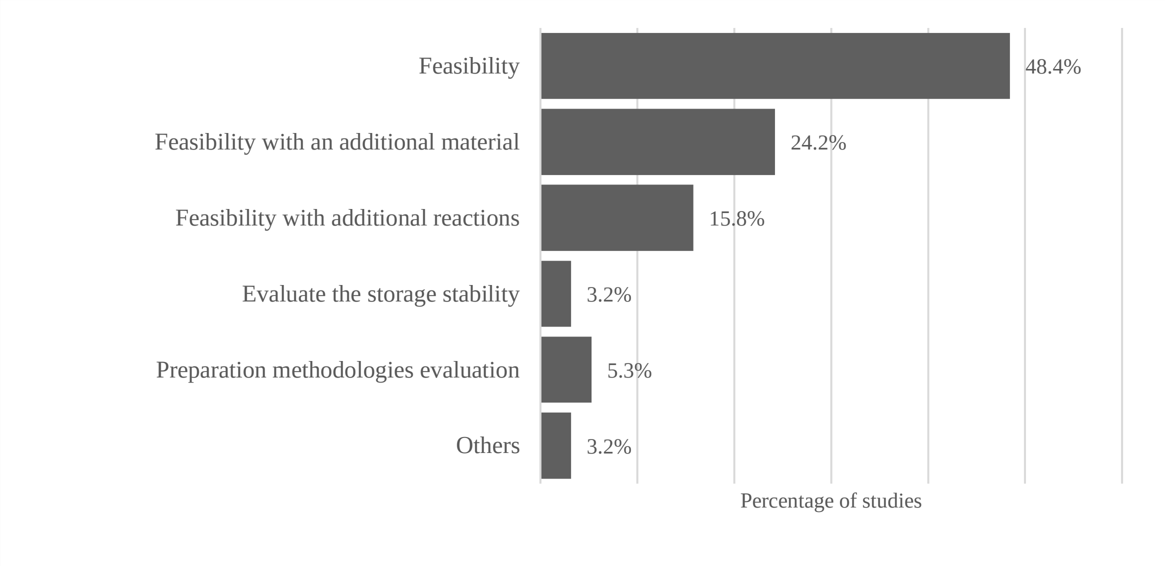


Figure 4. Summary of reviewed articles' objectives.

3.2 Plastics addition to bitumen overview

Although the main types of plastic studied as bitumen additives have been those that are commonly found in municipal solid waste, several studies have also experimented with other not so common plastic types. The plastics most used in the reviewed articles are low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyethylene terephthalate (PET), and polypropylene (PP), which correspond to 34%, 22%, 12%, and 11% of the total studies, respectively. These proportions correspond well to the percentage of waste generated for each of these plastics. Because these plastic types are commonly found in everyday objects, such as plastic bags, packaging, bottles, and clothing, and they represent most of the total plastic that goes to landfill(EPA, 2019), it was not unusual that the majority of the studies employed them. Alternatively, several articles have also investigated unconventional plastic wastes, such as Polyurethane (PU) (Salas and Pérez-Acebo, 2018), polyacrylic (Mohd Hasan et al., 2016), acrylonitrile butadiene styrene (ABS) (Razali et al., 2018) and plastic e-waste (Shahane and Bhosale, 2019; Yang et al., 2013).

Plastics may undergo one or a combination of pretreatments prior to addition to bitumen. Pretreatments may include physical, chemical, pyrolytic, and irradiative processes. The plastic pretreatment techniques mainly studied by researchers were physical (83%), which includes grinding and shredding, and those associated with chemical reactions (11%). These chemical reactions were mainly aminolysis and glycolysis reactions. Padhan and Gupta (2018) and Padhan et al. (2018a), for instance, used ethanolamine (EA) and ethylenediamine (EDA) to create an amylolysis reaction on PET, resulting in two types of additives: bis(2-hydroxyethyl) terephthalamide (BHETA) and bis(2-aminoethyl) terephthalamide (BAET). Similarly, Leng et al. (2018a) and Leng et al. (2018b) experimented with additives formed from the aminolysis of PET through the addition of triethylenetetramine (TETA), and Behl et al. (2014) added modifiers to the polyvinyl chloride (PVC) to increase the homogeneity of the polymer-bitumen mixture. Alternatively, Gürü et al. (2014) investigated the effect of PET after having a glycolysis reaction. The glycol and catalyst elements for this last study were propylene glycol and titanium butoxide (TB). Researchers in only two studies (4% of the studies) employed pyrolytic reactions. Yang et al. (2013) experimented with the heavy fraction pyrolytic oil of circuit boards and Avsenik et al. (2016) studied the plastic mix pyrolytic oil addition to bitumen. Additionally, another unusual pretreatment method employed in recent years was irradiation. The two articles that employed this technique were Ahmedzade, P. et al. (2014) and

Ahmedzade, Perviz et al. (2014). In their articles, they used gamma irradiation to strengthen the bonds between the plastic and the bitumen.

In addition to the previous innovative pretreatment methods, another new approach in the mixing of bitumen and plastic is to include other materials in the mix; for example, combinations of plastic waste with styrene–butadiene–styrene (SBS), crumb rubber (CR), and oil (Figure 5). These materials appear to mitigate some of the common drawbacks resulting from the plastic and bitumen particles' interaction. SBS, for example, is a copolymer that can improve the performance of PMB(Swamy et al., 2017), and although it has been previously used as a standard bitumen modifier, its major drawback is its high costs (Behnood and Gharehveran, 2019). For that reason, crumb rubber, which is derived from used tyres, is promoted as a cheaper replacement (Behnood and Olek, 2017) whereas oil, which is usually used engine or kitchen oil, is used to improve the workability of the bitumen. Interestingly, this oil can also be considered a suitable rejuvenator for bitumen that has been combined with reclaimed asphalt pavement (RAP) (Mamun and Al-Abdul Wahhab, 2018).

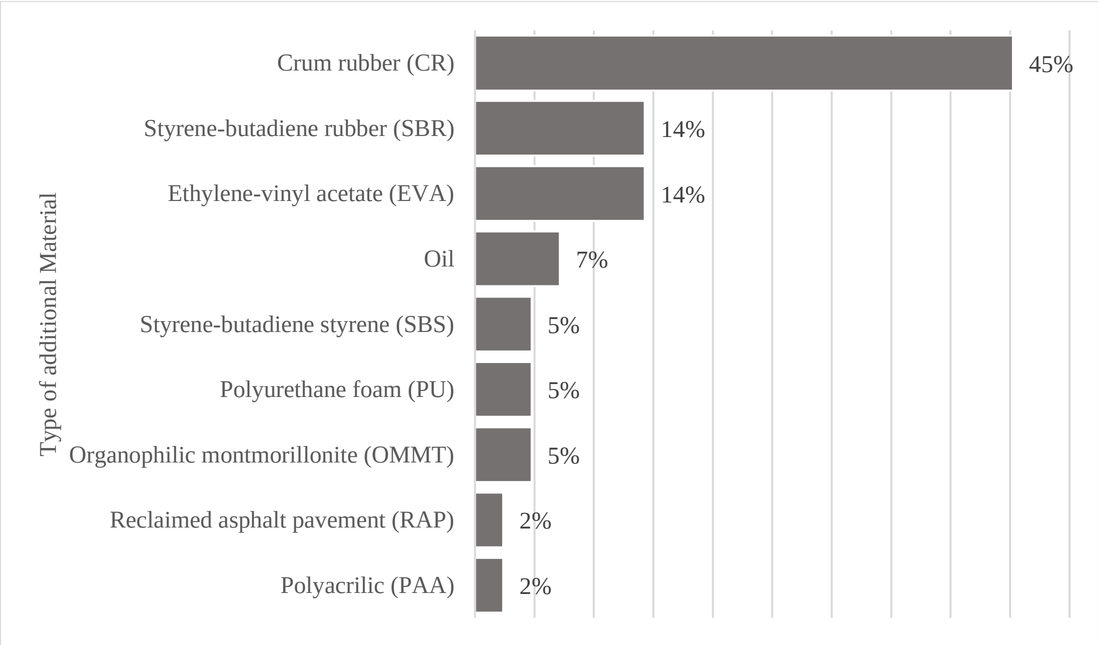


Figure 5 Additional materials used in combination with plastic waste as additives to bitumen.

During the mixing process, one of the parameters that vary the most, depending on the pretreatment method and the addition of another material, is the percentage of plastic addition. Among the articles, the percentage of plastic used for modifying bitumen was usually small (0.5% to 10% of bitumen weight) as shown in Figure 6. This range of values demonstrates that researchers have investigated this waste material as a bitumen modifier rather than an extender or substitute. We observed that when the plastic has gone through a grinding process, the percentage of plastic added is between 0.1% and 30%. This range tends to decrease when plastics are combined with other polymers, such as crumb rubber and SBS, or when chemical reactions are involved. The ranges for the later scenarios are 0.25–8% and 0.33– 10%, respectively. The reason for these low percentages in the samples with additional material seems evident; the other polymer presents already a detrimental effect on the bitumen properties, so by adding even a small amount of plastic, it could rapidly deteriorate the bitumen. However, in plastic with chemical reactions, it is not as obvious. A probable explanation is that the addition of a high amount of plastic would necessitate using higher chemical quantities, which increases the cost and complexity of the process, and it might not be economically feasible in a large scale.

Alternatively, plastic pyrolytic pretreatment is usually the process that adds the highest percentage of plastic waste. The percentage of plastic addition can be up to 50%. This high percentage of plastic additives is the major advantage of the pyrolysis method because it can treat a higher amount of plastic waste compared with other standard pretreatment methods.

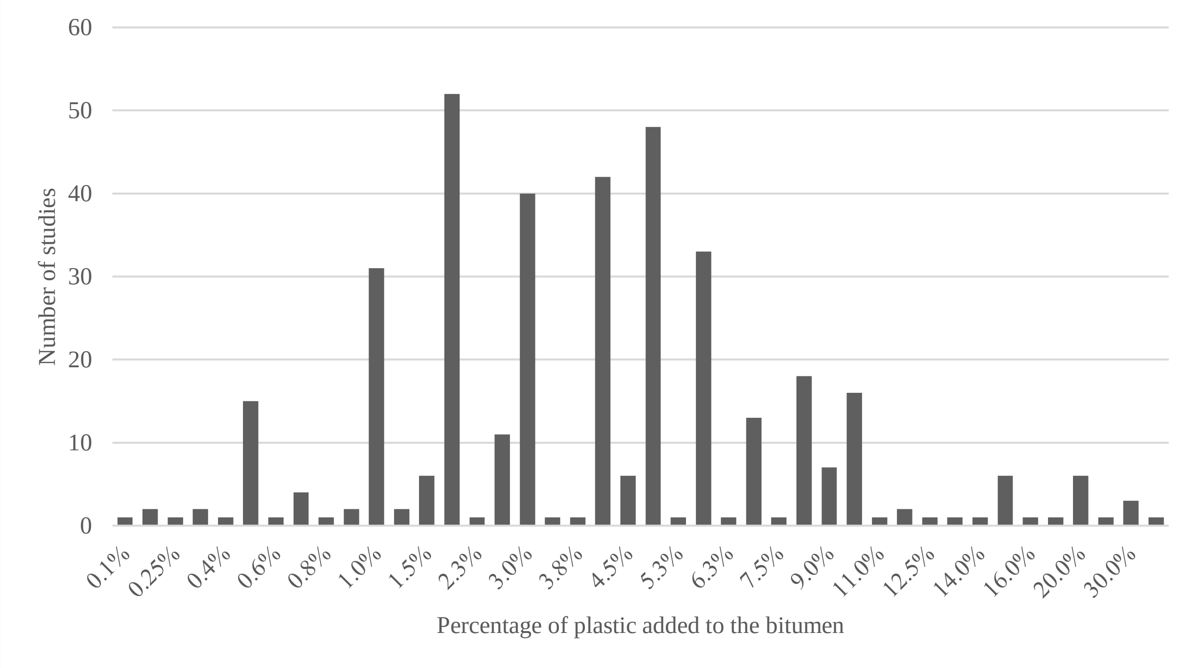


Figure 6 Percentages of Plastic Waste added to the bitumen and the corresponding number of articles for each percentage.

3.3 Effect of plastic addition on bitumen properties

For a more precise analysis of the effect of plastic waste in the bitumen, this section will evaluate the response of some of the basic bitumen properties after the addition of plastic waste. The present segment is divided into two sub-sections: conventional properties and Superpave properties (Superior performing asphalt pavements). The earlier will focus on the penetration, softening point and viscosity at 135°C, and the latter will evaluate the rutting, fatigue cracking, and cold temperature cracking resistance of the Superpave performance grading system.

3.3.1 Conventional Properties

Penetration

The needle test is used to measure the penetration property of the bitumen, and measures how resistant the bitumen is to hot temperatures. A needle enters the bitumen at a specific temperature, load, and length of time. The distance that the needle penetrates the bitumen sample is recorded as the penetration value, which indicates the hardness of a binder and identifies the climate where the binder is appropriate to use. Thus, high penetration values are commonly used in cold temperatures, and low penetration binders are used in hot environments. In the context of the present review, 54 articles studied the penetration trough the needle penetration method at 25 C°, which comprises a total of 379 observation.

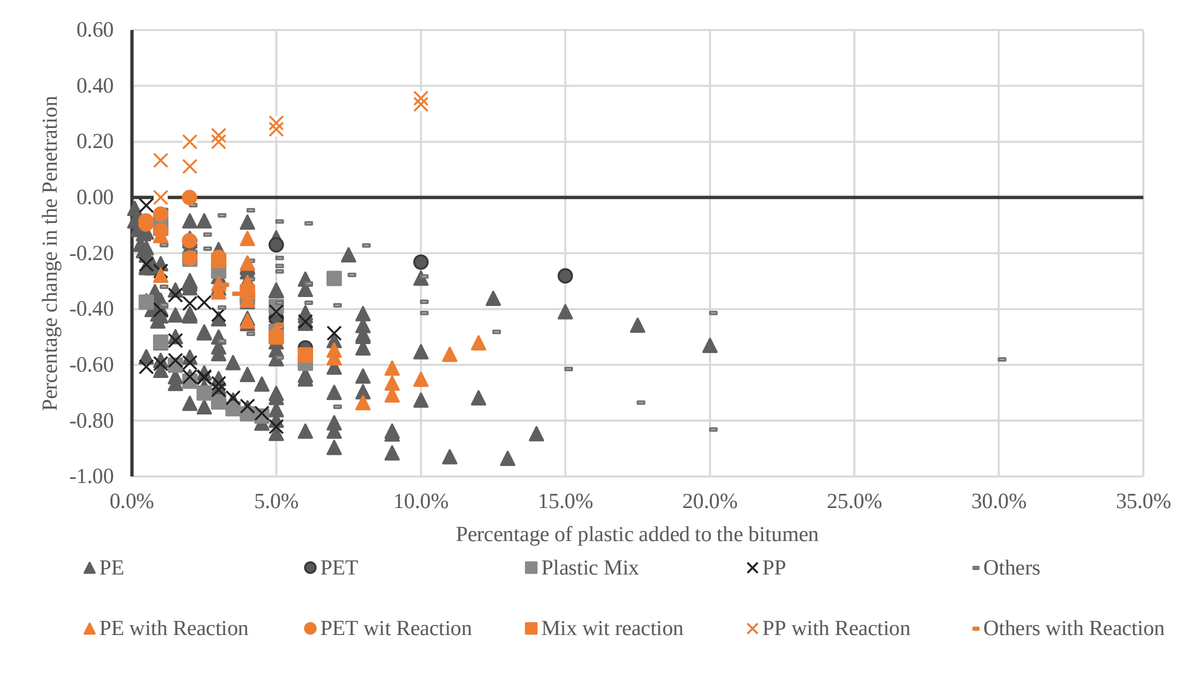


Figure 7 Change of the penetration due to the addition of plastic waste .

In general terms, the addition of plastic, regardless of the plastic type, reduces the penetration value and improves the PMB performance in hot temperatures (Figure 7). Fang et al. (2011) explained that the plastic waste in bitumen tends to absorb the low molecular components of the bitumen, provoking a swelling in their structures and a movement restriction between the molecules inside the asphalt, which will result in a decrease in the penetration of the bitumen. Without considering plastic waste with chemical reactions, the range of the penetration change is from -1% to -80%. The lowest variation in penetration, -1%, was reported by Yang et al. (2013). The first possible reason for this small change is that they used plastic pyrolytic oil, which is not as dense as unmodified plastic, as shown in the same article when this material is compared against styrene-butadiene rubber. The second reason is that they added a low percentage of the modifier, just 2%, so the effect was negligible. However, in the same article, when the addition of modifier is high, 10%, the change in the penetration variation tends to decrease further, -28%, showing a value more consistent with other studies. The most drastic decrease in penetration was reported by Jan et al. (2017) and Ahmedzade et al. (2017) with values of -85% and -84%, respectively. Both employed HDPE at high percentages, between 9% and 14%, and apart from these high values of plastic addition, there is no other apparent explanation of this excessive penetration decrease.
The bitumen seems to be more sensitive to PP, polyethylene (PE), and plastic mix than other plastic types. By observing the results of Figure 7, it is possible to see that some plastic types respond differently to the penetration change. PET and others, for instance, present a small change in the penetration by comparison to PP, PE, and plastic mix. In this study, *plastic mix* refers to the articles of Karmakar and Roy (2016), Suresh and Rao (2018), and Naskar et al. (2010), where a combination of HDPE, LDPE, and PP were employed. Thus, these results might suggest that PP, PE, and plastic mix could be the most appropriate types of plastic for establishing a PMB more resistant to hot temperatures.

Although some studies evaluated the same plastic type and percentage of addition, they presented different response in the penetration test, so it might be plausible to think that other factors are affecting the change in penetration. Ameri and Nasr (2017) studied higher plastic percentages

(5%,10%, and 15%) of PET, and surprisingly, they presented less penetration variation than Silva et al. (2015), who experimented with PET at 4%, 5% and 6%. A possible explanation is that the utilisation of devulcanised PET by Ameri and Nasr (2017) might have modified the penetration response. Devulcanization, in this context, refers to the process of invert the vulcanisation process that polymers endure for being converted into more lasting materials. Alternatively, this same behaviour occurs in research by Mahmood et al. (2018), who studied the effect of PVC on the penetration and softening point properties. By comparing their article with other researchers who also investigated PVC at similar percentages but reported different penetration results (Arabani and Yousefpour Taleghani, 2017; Behl et al., 2014; Köfteci et al., 2014), there were no obvious explanations. Mixing properties or external factors, which were not reported in Mahmood et al. (2018), might be the cause.

Interestingly, only one article presented an increase in penetration. Regarding those polymers that were chemically modified, almost all of these articles presented consistent results with the unmodified plastic output—a negative penetration change after the plastic addition. However, only one study by Gürü et al. (2014) produced distinctive results where the penetration increased. In their research, penetration increased due to the addition of two types of materials produced from the glycolysis of PET: Thin Liquid Polyol PET and Viscous Polyol PET. Thus, this means that the only bitumen that could present a detrimental effect at hot temperature is the one that is modified with the glycolysis of PET.

Softening Point

The softening point, which measures the consistency of the bitumen, tends to increase after the addition of plastic waste. The equipment employed to measure the softening point is the ring-and-ball apparatus, which measures the temperature at which the bitumen cannot resist a steel ball of 3.5 grams. This property is considered an approximation of the binder’s high temperature and permanent deformation resistance. In the present review, 53 articles assessed the softening point (376 observations), and the normalised results are presented in

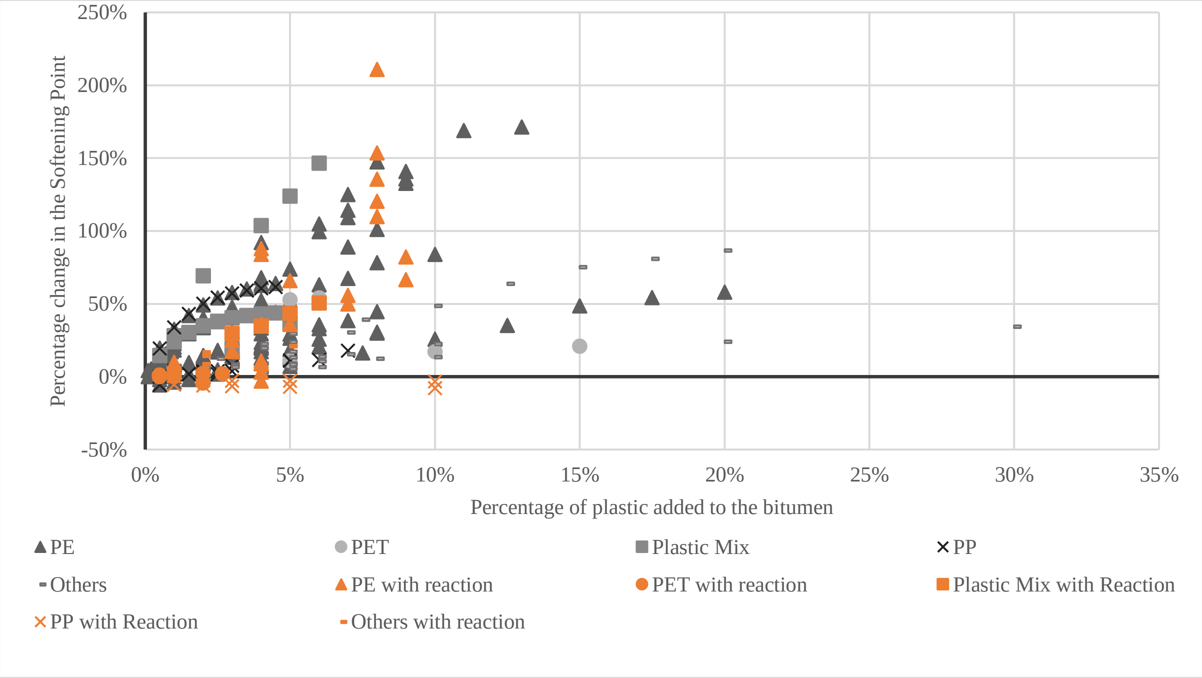


Figure 8. In general, the addition of plastic waste increases the softening point value, even when the percentage of addition is small. This increase in softening point is a result of the formation of a

polymeric network in the bitumen, which occurs after the polymer is thermally decomposed into the bitumen (Karmakar and Roy, 2016; Shirkavand Hadavand, 2010).

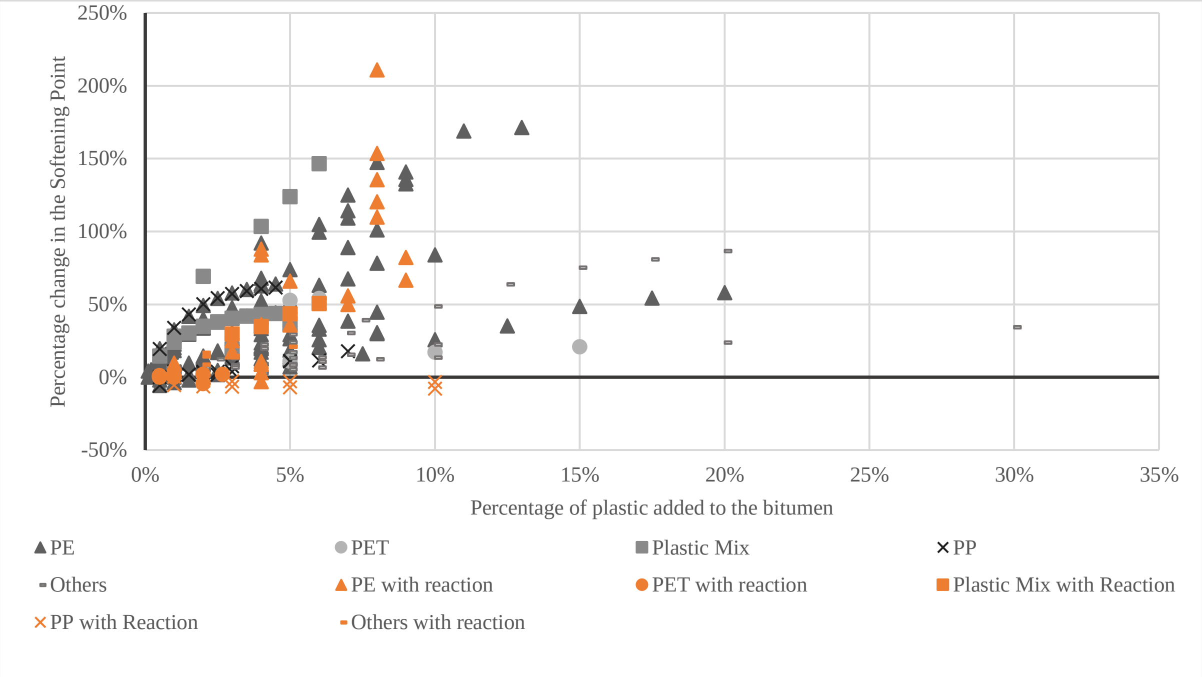


Figure 8 Change of the softening point n due to the addition of plastic waste .

In respect to softening point sensitivity, four articles that studied the addition of plastic mix (Suresh and Rao, 2018), PE (Ahmedzade et al., 2017; Zhang et al., 2016), and PP (Karmakar and Roy, 2016) presented drastic increases after adding small percentages of plastic waste. This result is in agreement with the review prepared by Brasileiro et al. (2019b), who also identified these plastics as the most sensitive in terms of the softening point. Although no conclusive explanation for these materials' responsiveness is found, we could infer that the internal structure of the polymers could play a role. Interestingly, these studies also display the highest effect on the penetration property, which corroborates the relationship between softening point and penetration. Two reasons explain this affinity. First, penetration is a property that is highly related to viscosity, and viscosity is a direct influencing agent of the softening point property(Thom, 2013). Second, as for penetration, softening point measures the susceptibility of the bitumen at hot temperatures, so one expects that both results are agreeable.

As was the case for penetration property, some studies that evaluated the same plastic type and percentages of addition presented different results in the softening point. Elements such as experimental conditions and polymers' characteristics might have influenced this softening point response. In

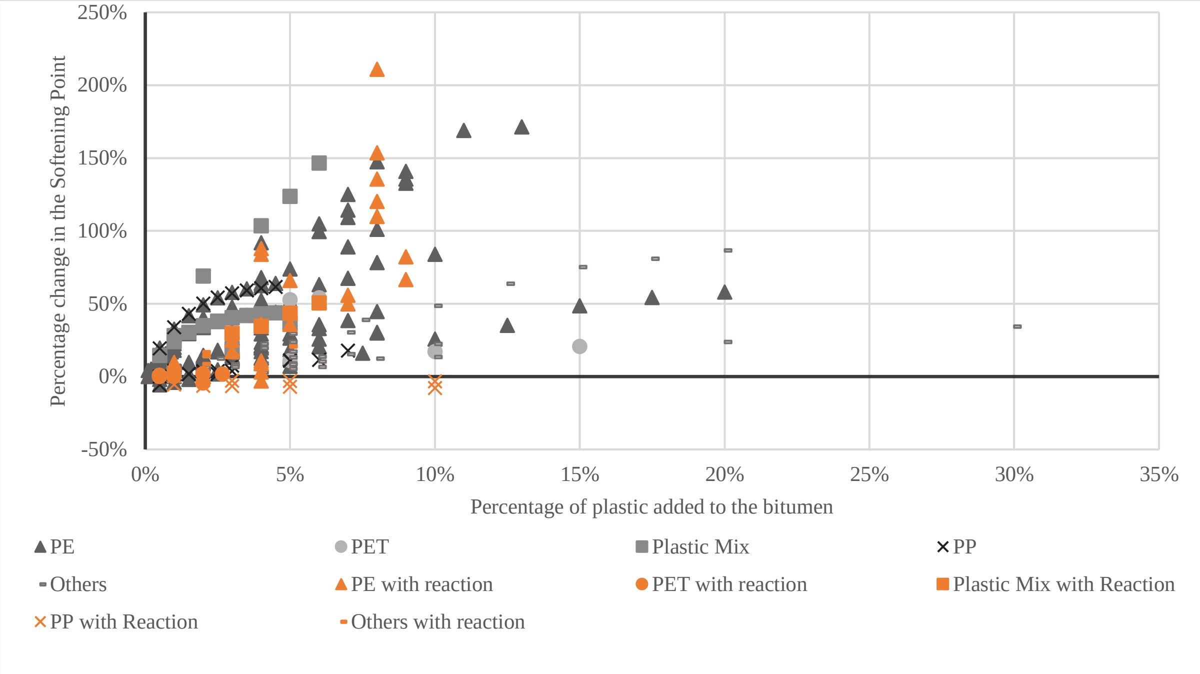


Figure 8, these differences are more evident in plastic mix and PP. With respect to plastic mix, this divergence is due to the different plastic types and proportions used by each article. For instance, Suresh and Rao (2018), whose plastic mix article presents the most significant change in softening point, added to the bitumen a combination of PET, PVC, PP, HDPE, and LDPE, while Naskar et al. (2010) and Karmakar and Roy (2016) employed a more limited type of plastics. In respect to the PP results, the main dissimilarity is between the article of Appiah et al. (2017), which presents the most significant variation in softening point, and Karmakar and Roy (2016). The explanation for this inconsistency is unclear; however, we still believe that the parameters during the mixing procedure or the characteristics of the waste might have influenced the results. By studying those two articles, one can infer that the shear speed and the type of PP waste, for instance, are some of the parameters that might have caused this disparity. While Karmakar and Roy (2016) employed plastic cups and shear speed of 3,800 rpm, Appiah et al. (2017) studied PP plastic bags at a lower mixing speed of 120 rpm. Other properties not mentioned in both articles, such as PP particle size, could have also influenced these results.

Regarding plastic wastes with additional reactions, apart from one article, all studies presented similar softening point variations to those articles that employed unmodified plastic waste. As was the case for penetration property, the article with different results was Gürü et al. (2014). There are two possible reasons to this disparity. First, thin liquid polyoil PET (TLPP) and viscous polyoil PET (VPP), the two modified plastics added in the research present lower penetration value and softening point than the virgin polymer. Thus, when TLPP and VPP are mixed with the bitumen, they change the consistency and internal configuration of the mixture, which might provoke the different results in softening point and penetration. Second, the consistency and interior characteristics of TLPP and VPP might alter the bitumen properties differently. Internally, when TLPP and VPP are mixed with the binder, they do not present the same effects of the other plastics that absorb the lightest portion of the bitumen; instead, they might be interacting differently. This type of behaviour would permit the smooth movement of the particles within the mixture, causing the unusual response in the penetration and softening point values.

One of the most common property that is strongly related to the softening point, and is mentioned by authors, is the storage stability. Poor storage stability occurs when PMB becomes a biphasic material, leaving the plastic and bitumen prone to separation (Zhu et al., 2016). Generally, for measuring this property, a bitumen sample is stored in an aluminium tube, and the difference between the softening points at the top and bottom sections of the tube is an indicator of storage stability (Nouali et al., 2018). The sample displays positive storage stability if the difference between these two values is less than 2.5°C(Fu et al., 2007). Values higher than 2.5°C will produce bitumen that require continual mixing, and thus higher overall costs. In the present review, 20 articles evaluated the storage stability property in PMB.

Among the studies that evaluated the storage stability, 73% showed a detriment in this property, and researchers determined that the main factors affecting it were the plastic-type and plastic content(Behnood and Gharehveran, 2019; Fang et al., 2014; Kalantar, Z. N. et al., 2012; Leng et al., 2018a; Nasr and Pakshir, 2019). In terms of plastic-type, the comparative study of Costa et al. (2013) found that HDPE and LDPE presented a more significant storage stability deterioration than Acrylonitrile butadiene styrene (ABS) and crumb rubber, two of the most common bitumen modifiers, and that the plastic particle size could exert some influence on this property. Fang et al. (2014) also found that other experimental parameters, such as shear rate and temperature, could also affect the final binder's storage stability. In this study, researchers suggested that the optimum experimental design of PE modified bitumen would include a shear rate of 2750 rpm, a temperature of 150°C, a shear time of 90 minutes, and a plastic content of 4%. In terms of percentage of addition, Ameri and Nasr (2016) found that small percentages, even 5%, present an adverse effect on the binder's storage stability. Similarly, Fuentes-Audén et al. (2008) explained that the addition of more than 5% reduces the workability of the mixture and produces a binder more expensive than other conventional polymer-modified bitumen. Thus, it is not surprising that the most common percentages of plastic studied in the past ten years were within a small range of 1% to %5.

Some solutions for this detrimental effect have been the addition of organic compounds, such as phosphorus compounds(Giavarini et al., 1996) or hydrophobic clay minerals(Zhu et al., 2014), to change the density of the polymer, by employing chemical reactions such as sulphur vulcanisation (Wen et al., 2001; Zhang et al., 2011) or by changing the plastic particle size. In our review, only six articles presented results below the 2.5°C limit(Fang et al., 2014; Köfteci et al., 2018; Leng et al., 2018a; Padhan et al., 2018b). From these studies, Padhan et al. (2018b) and Leng et al. (2018a) stood out due to the inclusion of chemical additives in the plastic, including cross-linking and reactive polymer-based additives and ethanolamine, respectively. In their studies, they stated that the chemical additives prevented the separation of bitumen and plastic and concluded that these reactions could solve the stability issue of PMB. Alternatively, Yu et al. (2015) proved that the addition of a small percentage of organic montmorillonite (OMt), 0.3% of bitumen weight, also improves storage stability. Although these techniques seem appropriate to improve the workability of the binder, in the future, it would be necessary to evaluate their associated economic factors to more clearly compare and understand the cost increase in the PMB. It is also important to evaluate the effect of these additives on the durability of the binder.

Alternatively, another solution that does not involve a chemical reaction is the reduction of particle size. Shahane and Bhosale (2019), for instance, experimented with powder e-waste and demonstrated that this plastic configuration did not present storage stability issues, even when the percentage of addition is relatively high, 6% of addition. Similar results were reported by Köfteci et al. (2014), who experimented with 5% PVC powder addition, and Costa et al. (2013).

To sum up, the addition of plastic waste is an adequate approach for roads development in hot environments, although its addition should be limited due to possible storage stability issues. The results in penetration and softening point have confirmed that PMB is an appropriate bitumen that can be used in hot climates. However, one must be careful with the excessive addition of plastics, because this can cause storage stability issues, which can affect the workability and increase the costs. Having said this, it is critical to find a balance between hot weather resistance and workability properties by selecting the appropriate plastic-type and by finding the most effective percentage to add.

Viscosity

Viscosity is a measure of the resistance of bitumen to deformation, measured using a rotational viscometer at different temperature ranges. For the present analysis, a temperature of 135°C was studied because it corresponds to the mixing temperature of the bitumen and is the most common value measured by studies. A total of 28 articles evaluated the viscosity at 135°C in recent years, which represents 207 observations.

Overall, the addition of plastics, regardless of the type, increases the bitumen viscosity due to the interaction between plastic and bitumen particles. The addition of plastic waste, regardless of the type or plastic content, tends to produce a PMB with higher viscosity. At the polymer level, Sun and Li (2010) mentioned that because the plastic particle tends to swell after absorbing the lightest portion of the bitumen, it results in bigger plastic particles that prevent the internal movement of the mixture. Alternatively, at the mixture level, Farahani et al. (2017c) and Al-Abdul Wahhab et al. (2017) explained that the increase of viscosity occurs due to the creation of a three-dimensional network within the bitumen. This network creates an internal movement resistance and thus an increase in the viscosity.

As a general rule, this viscosity at 135 °C should always be below a specific limit, usually 3 Pa.s, so the bitumen can be efficiently injected, to enable thorough coating of the aggregates. Thus, PMB with a viscosity above 3 Pa.s is challenging to add to the asphalt mix and increases the costs due to higher energy requirements. In our review, 6% of the samples did not meet the 3 Pa.s limit.

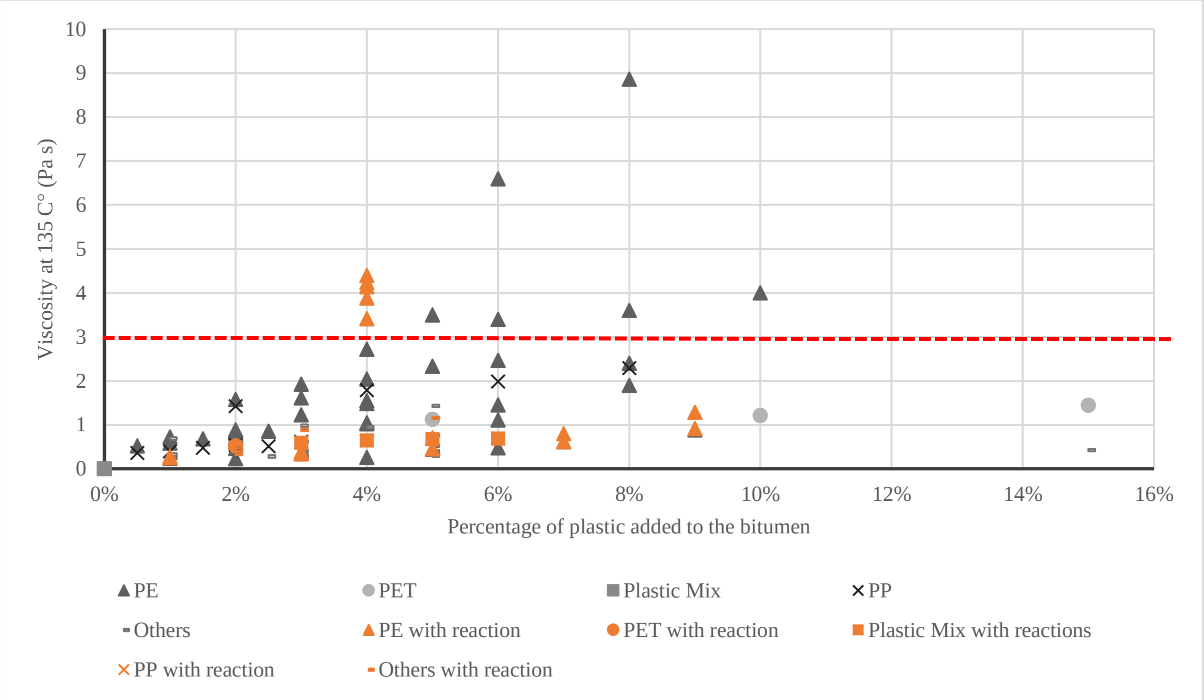


Figure 9 Change of the Viscosity at 135 °C due to the addition of plastic waste .

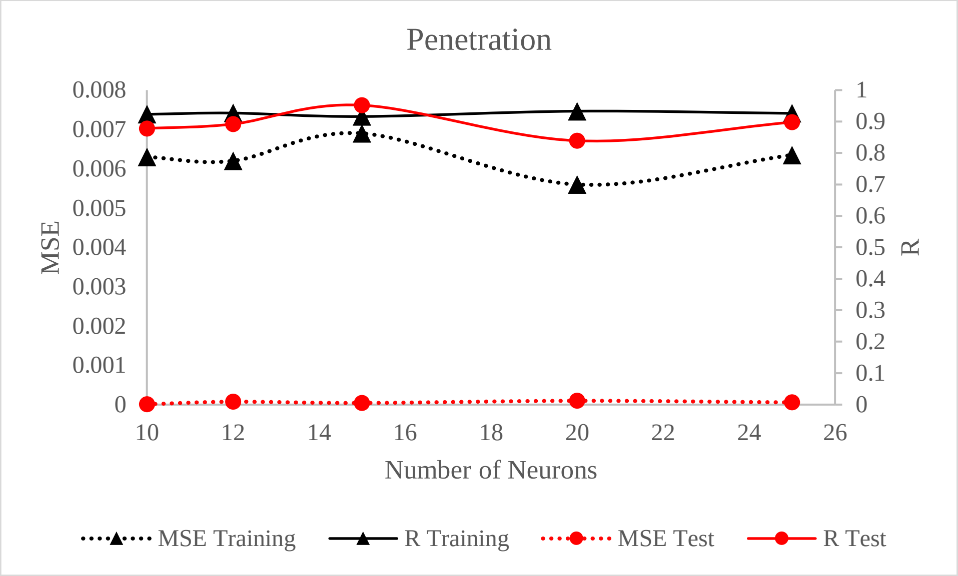
From the sample, PE is the material with the highest effect on the viscosity property, followed by PP and PET. As can be seen in Figure 9, the plastic waste that has the highest impact on the viscosity parameter is PE, especially when the content is over 5%. Indeed, after adding 5% of PE, four articles showed viscosity values above 3Pa.s. (Al-Abdul Wahhab et al., 2017; Hu et al., 2015; Lin et al., 2019; Yan et al., 2015). The article with the most significant number of samples above the 3Pa.s limit was by Al-Abdul Wahhab et al. (2017). In this article, they concluded that contents of 4% and 6% for HDPE and LDPE, respectively, represented the limit where the viscosity is within the appropriate range. This percentage is not in agreement with Lin et al. (2019), who found that the addition 8% of PE may still comply with this 3Pa.s threshold. Again, the different results between these two articles might be caused by different experimental parameters and plastics' nature. Contrary to PE, the addition of PP does not substantially affect the viscosity property; however, this observation is based on a small sample— just two articles(Al-Abdul Wahhab et al., 2017; Appiah et al., 2017). Similarly, there was just one article that evaluated the effect of PET on viscosity (Ameri and Nasr, 2016), and although it is the material with less effect on the viscosity, this result might not be conclusive due to the limitation of the sample size.
If plastic is added with additional material, the resultant PMB viscosity tends to be above the 3 Pa.s limit, whereas if the plastic has been chemically modified, the resultant viscosity is usually below the 3 Pa.s limit. The combination of plastic and crumb rubber or SBS produces a PMB with a significant increase in the viscosity parameter, up to the point that 50% did not comply with the 3 Pa.s limit(Al-Abdul Wahhab et al., 2017; Farahani et al., 2017b; Yan et al., 2015; Yang and Cheng, 2016; Zhang and Hu, 2016). This significant increment in viscosity is generated by the internal interactions of the components, the high quantity of modifiers added to the bitumen, and the structural reinforcement created by the polymers(Al-Abdul Wahhab et al., 2017). On the contrary, when the plastic added has been chemically modified, the viscosity of the resultant binder is low, even when the percentage of addition is above 5% (Ahmedzade et al., 2015; Ahmedzade, P. et al., 2014; Behl et al., 2014).

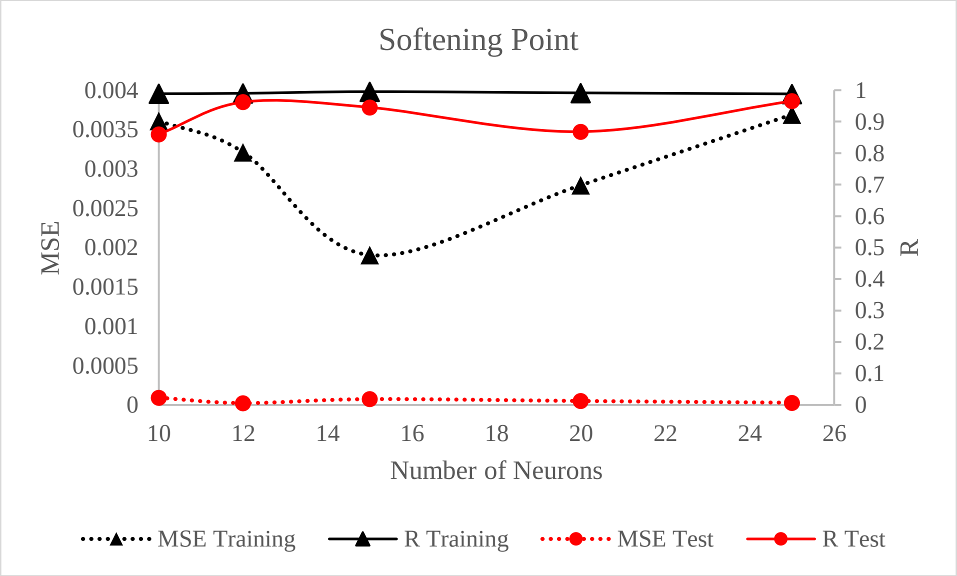
As was the case for the softening point and penetration properties, we also found in the case of viscosity that although many articles have experimented with the same plastic type and the same percentage of additions, researchers presented different results. Some articles with these different results were Al-Abdul Wahhab et al. (2017), Hu et al. (2018), Hu et al. (2015), Köfteci et al. (2018), and Lin et al. (2019). We initially inferred that these divergences occurred due to different experimental parameter; however, this interpretation is not definite unless a more in-depth study on the properties effects is completed. For this reason, we believed it pertinent to prepare the next statistical analysis for quantifying the impact of experimental parameters on the penetration, softening point, and viscosity properties of the PMB.

3.3.2 Neural Network Models

At the moment, although some articles have applied machine learning in the road construction field (Shafabakhsh et al., 2015; Tapkın et al., 2009, 2010; Yilmaz et al., 2011), none of them has modelled the effect of plastic addition or experimental parameters on the bitumen. Additionally, there are a limited number of studies that have evaluated the relation between experimental parameters and bitumen modified with plastic waste. As of to date, only Fang et al. (2009) have attempted to study the correlation between the mixing temperature and PMB properties. Although the authors concluded that high mixing temperatures increases the softening point and decreases the penetration of the resultant bitumen, the study did not consider other properties that can affect the resultant bitumen. Therefore, in this section, we seek to introduce a new modelling approach using ANN and extend the work of Fang et al. (2009) to include the impact of other experimental factors on the three conventional characteristics of bitumen (penetration, softening point and viscosity). In the preparation of these models, studies that used chemical and thermochemical pretreatment of plastic prior to the addition to bitumen were excluded.

After cleaning the data, the datasets collected for each property consisted of 289, 287 and 280 records for the penetration, softening point and viscosity, respectively. Each dataset was divided randomly into two sets, training (90%) and testing (10%), the validation set is not needed for the Bayesian regularization (BR) because it has its inbuilt regularization method. An ANN model was built for each of the three bitumen properties. Each of the models was composed of an input layer, a hidden layer and an output layer. Following the empirical rules of ANN, the input layer had 12 neurons, a neuron for each feature and one neuron in the output layer corresponding to the property being modelled. To select the optimal number of neurons in the hidden layer, the performance of the network was tested with a number of neurons ranging from 10 to 25. The results of this exercise are shown in Figure 10. The best performance was achieved with 12 neurons in the hidden layer in all three cases. It is important not to use more than necessary neurons to avoid overfitting. Therefore, the ANN models for the three properties. Consequently, a Bayesian Regularized networks which have 12:12:1 architecture (input layer: hidden layer: output layer) were selected.


Penetration
MSE
R
Number of Neurons
MSE Training
R Training
MSE Test
R Test


Softening Point
MSE
R
Number of Neurons
MSE Training
R Training
MSE Test
R Test

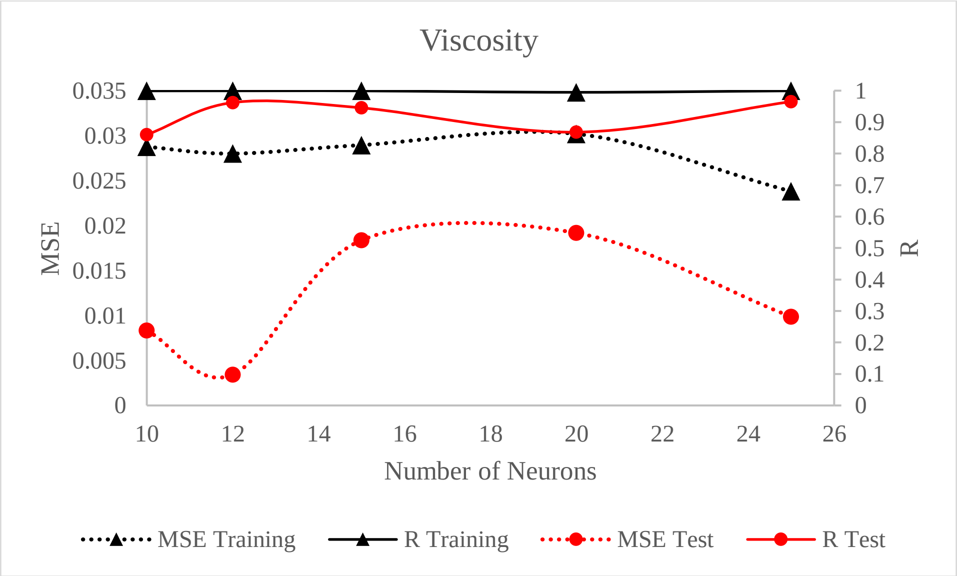

Viscosity
MSE
R
Number of Neurons
MSE Training
R Training
MSE Test
R Test

Figure 10. Optimisation of the number of neurons in the hidden layer.

Penetration

Feature analysis, shown in Figure 11, reveals that there is no strong interaction among features. It further shows that the percentage of PE addition has the highest influence on the penetration property of bitumen, followed by PP and PET. The negative sign further confirms the observations that increased addition of PE would reduce the penetration property of bitumen.

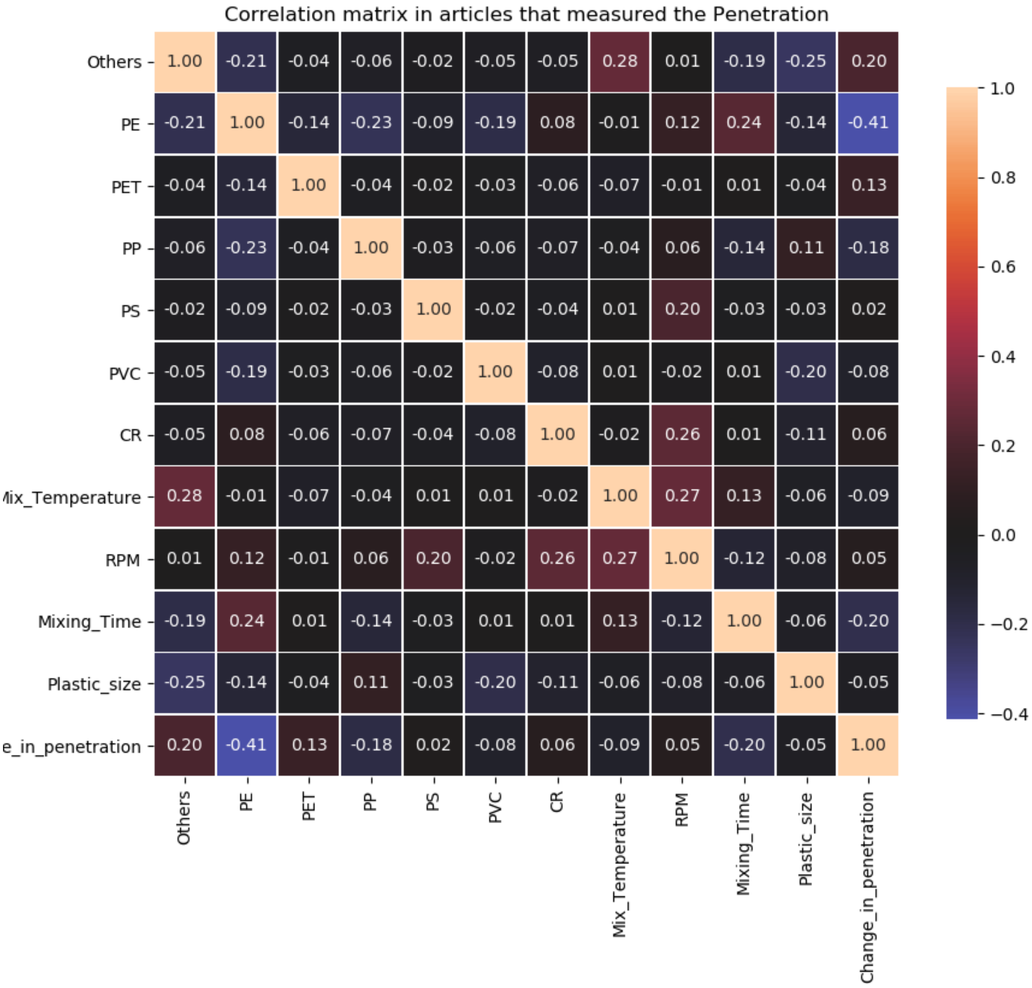


Figure 11. Correlation Matrix among features and penetration change.

Another literature review has also concluded that indeed PE, PP and PVC display strong effect on the penetration parameter (Brasileiro et al., 2019a). Concerning experimental conditions, the parameters that seem to present some influence on the penetration change are the mixing temperature, mixing time, and plastic particle size; however, their correlation results were not too strong. These results prove that although these parameters exhibit some effect on the penetration change, their impacts are small, and thus, there might exist other parameters that explain more accurately the divergences in the penetration results. Among the articles evaluated in the present review, Fang et al. (2009) was the only study that assessed the impact of the temperature on the resultant bitumen penetration. In their article, the penetration decreased when the mixing temperature was increased. Fang et al. (2009) explained that when the temperature rises, the plastic polymer starts absorbing the lightest portion of the bitumen at a higher rate, creating swollen plastic particles that restrict the movement of internal molecules. In the same way, although there were no articles that have studied the effect of particle sizes in-depth, one can infer that when the plastic particles are larger, they tend to restrict further the internal movement of the modified bitumen components.

The ANN model has captured the expected effect of plastic addition on bitumen penetration. As can be seen from Figure 12, the model predicts a decrease in penetration. The model's predictions are reasonably accurate with R=0.923 and MAPE=0.233. Record 78 shows the maximum deviation (RE=-13.71), to understand the reason behind this deviation, we inspected the record. The record represents the addition of 0.5% PP. There are three records in the dataset that has this percentage of PP. The reported change in penetration in response to this percentage of PP addition for the three records was very different (-0.0286, -0.2398 and -0.6071). Therefore, the predicted change by the model for this record (-0.4204) is well within the reported range. Similar observations were also made about the other records.

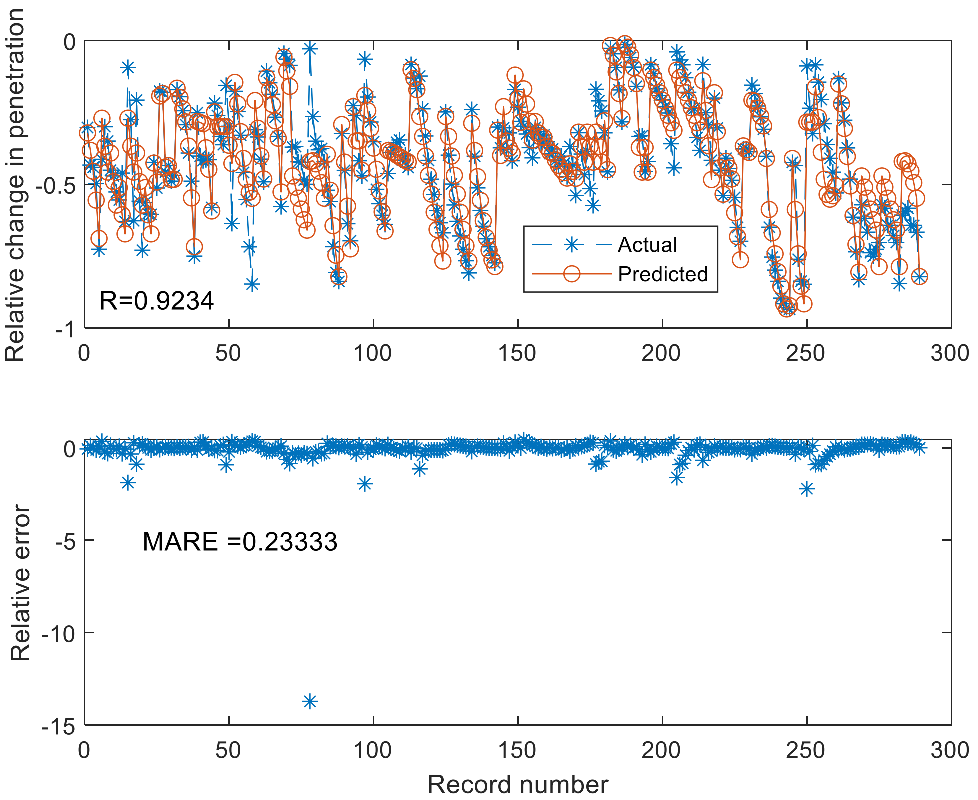


Figure 12. ANN model predictions and relative error in penetration.

Softening point (SP)

Table 1 shows the coefficient of correlation between the different features and the change in softening point. It can be seen that among the plastics, PE exhibits the highest influence. The analysis also reveals that mixing time presents an effect influence on the softening point.

Table 1. Feature influence on the change in softening point

	Other plastics	*PE*	*PET*	*PP*	*PS*	*PVC*	*SBS*	*CR*	*Mix Temp*	*Mix. speed*	*Mixing Time*	*Plastic size*
Change in_SP	-0.16	0.46	-0.05	-0.08	-0.06	0.37	0.05	0.03	0.04	0.02	0.60	-0.05

This high value in PE was expected, and it confirmed the strong influence of these polymers on the softening point variation. PVC had the second largest influence on the softening point. Similarly, Brasileiro et al. (2019a) stated that PVC and ethylene-vinyl acetate (EVA) were the polymers with the highest impact on softening point. In respect to experimental properties, the two parameters that exert some effect on the softening point are the mixing time and the particle size. Indeed, when the particle size is larger, it facilitates the creation of a more rigid polymer network that might be affecting the softening point value. Regarding the mixing time, Babalghaith et al. (2019) demonstrated that the increase of mixing time provokes an increase in the polymer modified bitumen's complex modulus, and thus, its softening point. Babalghaith et al. (2019) explained that when the mixing time is high, it permits the dispersion of the polymer, which increases the bitumen stiffness. The feature analysis also show that the influence of different features is varied; while some of the features have a negative correlation, others have a positive influence. Therefore, it is possible to adjust the final softening point of the PMB to the desired value by varying the mixing conditions.

The ANN was able to predict the response in softening point as a result of the addition of different plastics and operating conditions, as shown in Figure 13. The correlation coefficient between the actual values and predicted values is 0.986, which means that the model is able to explain more than 97% of the variations in the response variable (softening point). Nevertheless, there are still some errors which appear to be large. One of the possible reasons for this is the omission of some other variables that could also be relevant for the model. We believe, for instance, that one of these missing variables could be the bitumen type. Indeed, by evaluating the article by Kumar and Garg (2011), it was found that the bitumen type can intensify the change in bitumen's properties after plastic addition. In this article, the bitumens employed were the 60/70 and 80/100 penetration grade, and some of the properties measured were penetration, softening point and ductility.

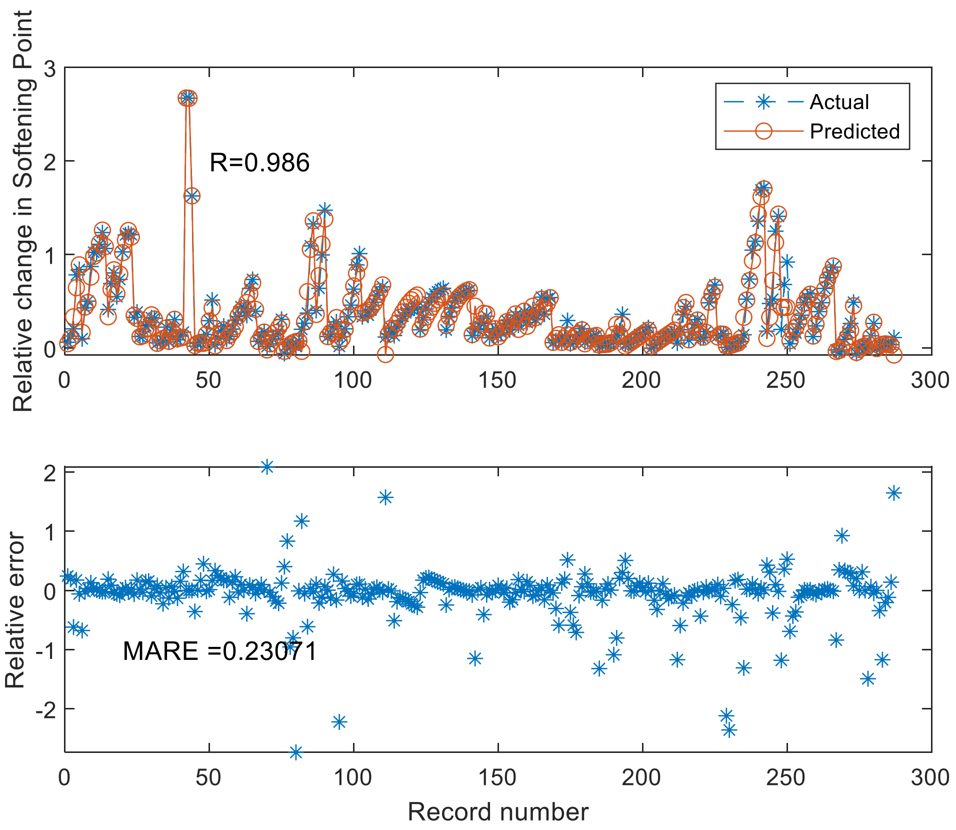


Figure 13 ANN model results and relative errors in softening point.

Viscosity

Table 2 shows the importance of the features on the change in viscosity of PMB. Crumbed rubber has the highest effect on viscosity, followed by PE and then PVC. Mixing speed and plastic particle size also exhibit influence on the viscosity of PMB. The effect of CR addition on the viscosity is expected after seeing that 50% of the samples that contained SBS or CR did not comply with the viscosity requirement (<3 Pa.s).

Table 2. Features influence on the change in viscosity of PMB.

	PE	*PET*	*PP*	*PS*	*PVC*	*SBS*	*CR*	*Mix Temp.*	*Mix. speed*	*Mixing Time*	*Plastic size*
Change in Viscosity	0.38	-0.05	0.00	-0.09	-0.13	-0.01	0.55	0.09	0.29	-0.03	0.24

Among the mixing parameters, shear speed and plastic size presented the highest correlation with the change in viscosity property. It is inferred that the influence of the mixing speed on the bitumen's viscosity occurs due to the change in the internal bitumen morphology. Previous studies that have evaluated the effect of mixing speed on the bitumen modified properties have also found some effect. González García and Herrera Nájera (2016), for instance, found that the increase of the mixing speed tends to increase the viscosity of bitumens modified with SBS. However, this same article found that small particles of SBS present higher viscosity results, which is in disagreement with the results found in Table 2.

The ANN model predicted the change in viscosity as a response to the addition of different plastic types, percentages and mixing conditions (Figure 14). The model has successfully predicted the changes in viscosity with high accuracy as indicated by R and MAPE values. As can be seen in Figure 14, there are two regions which exhibited higher relative error than the rest, these are traced to records 20 to 45 and 240 to 256. Upon closer inspection, the first group belong to records with a mix of PE and SBS; as discussed earlier SBS and PVC were shown to have a significant effect on bitumens softening point and viscosity. Upon the inspection of the predicted values, it was found that these are well within the reported range in the literature for the percentage addition. The second group represented bitumen modified with PVC, as discussed earlier, PVC had been shown to have a variable effect on bitumen's viscosity depending on its type. Once again, it was found that the predicted values are well within the range reported in the literature for the percentage addition of PVC. The variability may also be caused by not taking into account other factors that may influence bitumen's behaviour, such as bitumen type as discussed earlier. Therefore, we conclude that the model's predictions are valid and acceptable.

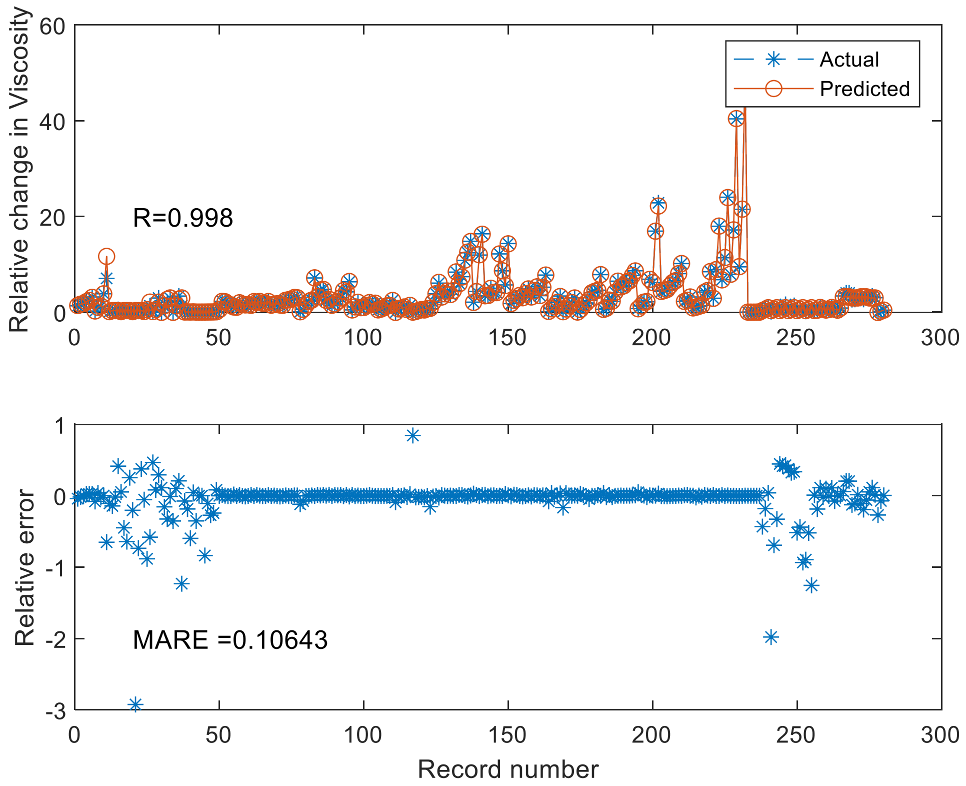


Figure 14 Models predictions of change in viscosity and relative errors.

Since 2009, many articles employed the penetration, softening point and viscosity to measure the effectiveness of a PMB; however, it is believed that these properties are not accurate enough to predict the bitumen performance in actual road conditions because of their empirical nature (Arshad and Qiu, 2012). As an alternative, the Superpave practice has created a grading system, performance grading (PG), for assessing the bitumen resistance to the three most common road issues; rutting, fatigue cracking and cold cracking. In the next section, these properties will be investigated.

3.3.3 Superpave properties and PG grading

One shortcoming of the conventional grading of bitumen is its inability to take into consideration the climate conditions and the ageing of the bitumen. To differentiate bitumen types, researchers have proposed three major grading systems; penetration grading, viscosity grading, and PG. Some limitations of the penetration and viscosity grading are the disregarding of the climate where the bitumen is applied, ageing processes, and their unsuitability for evaluating polymer modified bitumens (Mampearachchi et al., 2012). The PG, on the other hand, considers the climate conditions, and it creates a more realistic framework.

This system grades the bitumen with two numbers that reflect the high temperature and low-temperature performance. Thus, a PG 58-10 means a bitumen suitable for climates where the average seven-day maximum temperature is 58°C and minimum temperature is -10°C. Additionally, this grading system takes into consideration the viscosity parameter; for example, if a PMB presents a high resistance to hot temperatures, but it also has a high viscosity value (above 3Pa.s), it is rejected (AASHTO, 2016).

Rutting resistance

The rutting resistance is measured through a dynamic shear rheometer (DSR) that calculates two basic rheological parameters: the complex modulus (G*) and the phase angle (δ). These two values are part of an additional property named rutting factor, defined as G*/sinδ. This factor represents the rutting resistance of a binder to high and medium temperatures — higher G*/sinδ means high resistance, and it is the base of the binder's upper grading. An alternative approach for measuring the high-temperature resistance is through the multiple stress creep recovery (MSCR) test. For the present analysis, we focus on articles that employed the DSR approach because the sample was more significant than the MSCR test sample —21 articles used DSR versus eight which used MSCR—; however, we recommend to future researchers to evaluate rutting resistance under the MSCR because it is more accurate, and it better describes the potential of a binder (Yao et al., 2018).

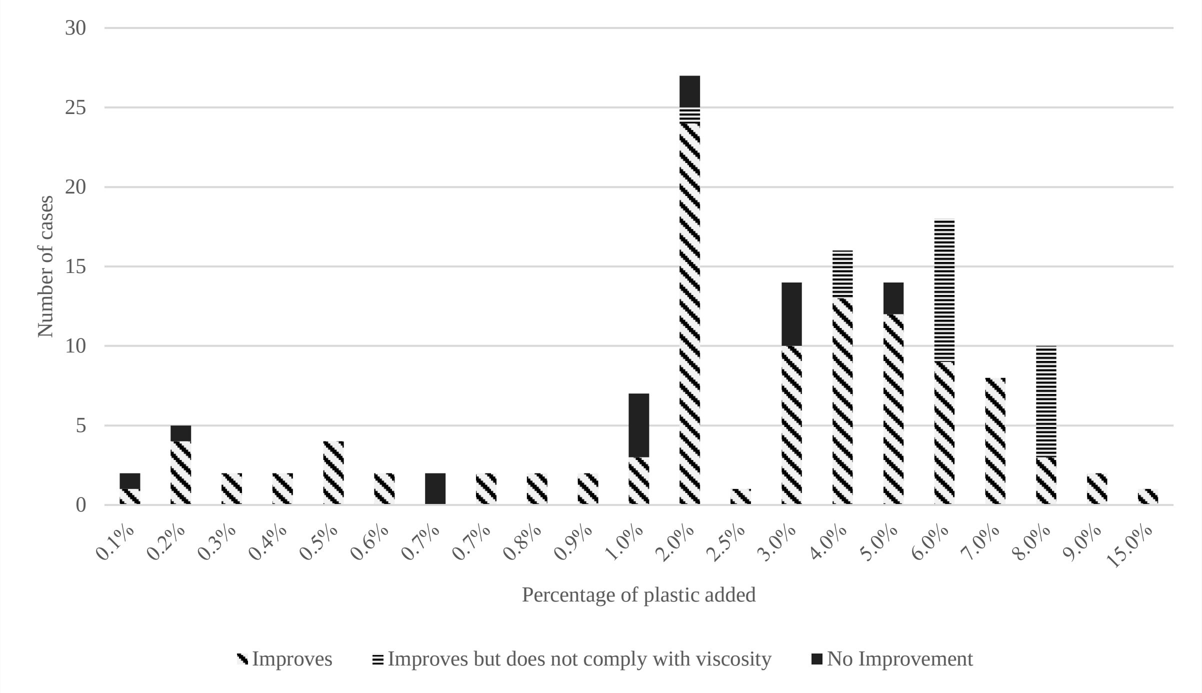


Figure 15 Effects of the addition of plastic waste on high-temperature PG-grading.

Figure 15 shows the response of bitumen to plastic addition classified into three classes: the PMB improves and becomes resistant to higher temperatures, it improves but does not comply with the viscosity threshold, and no improvement. Overall, the results of the articles showed that 75% of the samples improved their rutting resistance after the addition of plastic waste, 14% did not comply with the viscosity requirement, and 10% did not present any enhancement. Thus, although the rutting resistance improves, some viscosity issues could appear, especially when the percentage of plastic is more than 4%.

The increase in the stiffness causes the improvement in the rutting resistance, and it is mainly observed after adding PE, PP or PVC at high percentages. Most of the articles that resulted in PMB improvement employed PE (Al-Abdul Wahhab et al., 2017; Dalhat and Wahhab, 2017; Hu et al., 2018), PP (Al-Abdul Wahhab et al., 2017), and PVC (Köfteci et al., 2014). A possible explanation for this enhancement is that the polymer increases the stiffness of the bitumen, by rising G* and δ, thus produces a higher rutting factor. Interestingly, this effect is more evident when the polymer added is HDPE (Dalhat and Al-Abdul Wahhab, 2017), and when the percentage of addition is high (6%-8%).

The percentage of plastic addition was the leading cause of the non-compliance of the viscosity requirement. In the scenario where the sample improves the rutting factor but did not comply with the viscosity, two articles were present. The first article employed a combination of different plastic types; PP, HDPE and LDPE; with SBS (Al-Abdul Wahhab et al., 2017). In this study, the increase of the viscosity above 3Pa.s occurs because the samples were a combination of different plastic types and because the percentage of plastic was too high — more than 8%—. Similarly, the non-compliance of the second article was also caused because of the high addition of plastic(Dalhat and Al-Abdul Wahhab, 2017).

In the third possible result, no improvement, the samples were mainly PMB with a low percentage of plastic waste. This means that small quantities were not enough to alter the final upper grading of the binder. Kumar and Garg (2011) and Köfteci et al. (2014), for instance, presented no improvement in their samples when the percentage added was low — 0.2% of PE and 1% of PVC, respectively. Also, it is interesting to note that the article from Gürü et al. (2014), the one with chemical reactions and particular results in penetration and softening point, was among the articles that did not result in any improvement in the rutting resistance. In this study, the author explains that the addition of these two materials causes a decrease in G* and the stiffness of the binder, which has a direct impact on the rutting resistance. Another study that employed chemical reactions and did not improve the rutting resistance was Padhan et al. (2018a), and the apparent explanation of this result is the low percentage of plastic added, just 0.66%.

Although penetration and the softening point could partly predict the rutting resistance, they are not as accurate as of the rutting factor. The results of the rutting factor are a confirmation of what it was observed in the penetration and softening point results, so these conventional properties might have some relation. Other articles have also confirmed this. Partl (2003), for instance, found a negative correlation between penetration and G*. Also, Mashaan and Karim (2013), who studied the effect of crumb rubber in the bitumen, demonstrated the positive relationship between softening point and $G^*/\sin\delta$. Finally, it is essential to restate that although the penetration and softening point can partly describe the rutting resistance of a binder, these measurements should not wholly replace the rutting parameter (G^*/δ), or the MSCR tests, because they do not consider the rheological nature of the binder and the ageing process.

To conclude, it is noticeable that the addition of plastic waste has the potential to increase the upper limit of the PG grading. However, as it was seen in the conventional properties section, one must be aware that the exaggerated addition of plastic waste, above 6%, could compromise the sample due to viscosity issues. Additionally, it is noteworthy to recognise that the percentage of the addition of plastic waste should not be too small –not less than 2%–; otherwise, there will not be any improvement in the PG upper limit.

Fatigue resistance

The fatigue resistance is a measure of the binder's resistance to constant loadings after being induced to ageing processes. The equipment employed for this test is the DSR, and again, it measures the complex modulus (G*) and phase angle (δ), although the final-calculated component is the fatigue factor ($G^*\delta$). A bitumen with low fatigue factor has higher fatigue cracking resistance because it is less stiff, due to the lower G*, and more elastic, due to the lower δ.

As it happened with the rutting factor, some inconveniences are also associated with this fatigue factor. Researchers have argued that this parameter is not an accurate representation of fatigue performance because it does not report the accumulated damage of a binder (Bahia et al., 2013; Bessa et al., 2019; Nasr and Pakshir, 2019). Therefore, two other alternatives have been proposed: the linear amplitude sweep test (LAS) and the time sweep test (TS). Because the TS is time-consuming, researchers prefer to use the LAS; which is also more precise than the TS, as Johnson (2010)stated. For the present analysis, although it was preferred to examine those studies that employed the LAS, it was not possible because the sample was very small —just two articles (Hu et al., 2018; Nasr and Pakshir, 2019)—, so it was based on the DSR. It is important to note that the sample that employed the DSR was still limited, only eight articles, and none of them evaluated the viscosity. However, considering the limited number of articles that studied the fatigue resistance in the last ten year, DSR seems to be the most appropriate approach to identify the effect of plastic waste on this Superpave property.

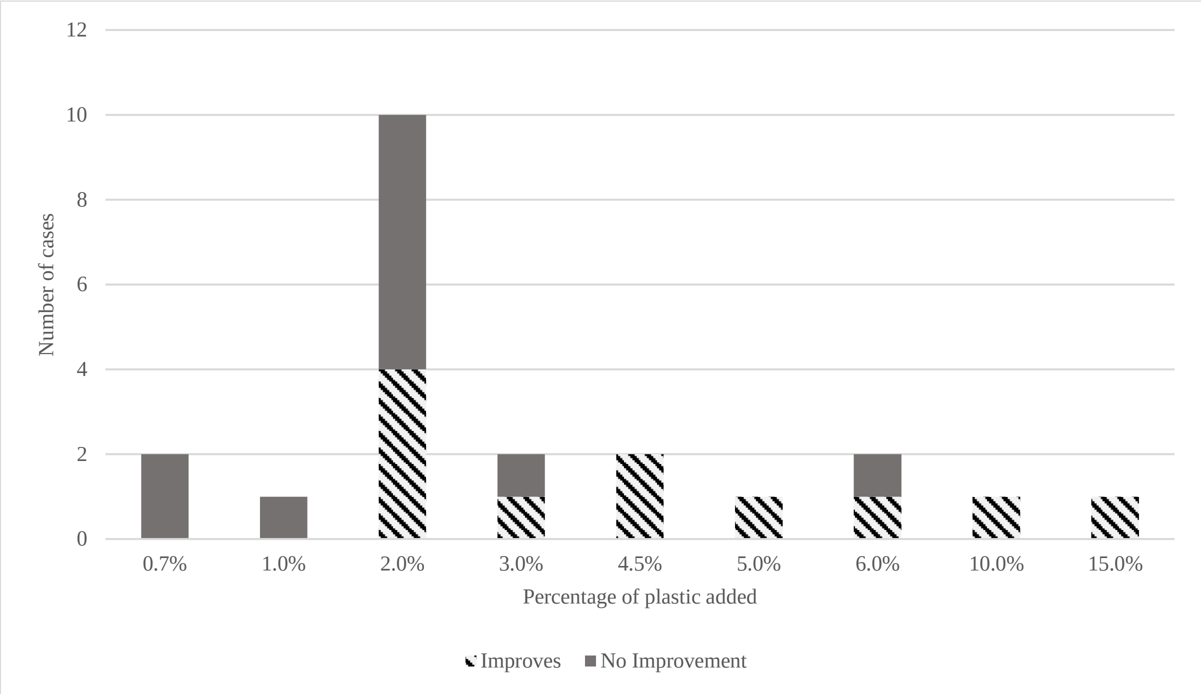


Figure 16 Effects of the addition of plastic waste on the fatigue cracking resistance grading.

In general, the addition of plastic waste improves the fatigue cracking resistance of the binders. Figure 16 demonstrates that the improvement of PMB in terms of fatigue resistance mainly occurs when the plastic's addition is 4.5% or greater. Most of the articles that present fatigue resistance improvement employed PET, PET with additional material; such as Crum rubber and reclaimed asphalt pavement (RAP)(Leng et al., 2018b; Nasr and Pakshir, 2019); and PP with a chemical reaction(Gürü et al., 2014). Following this, Leng et al. (2018b) explain that this improvement occurs because the polymer addition increases the tensile strength and elastic response in the bitumen —properties that are strictly related to G* and δ— and that the extra usage of specific chemical reactions, such as aminolysis processes, produce a final asphalt mix more suitable to dissipate the compact energy.
When the plastic is combined with crumb rubber or oil, the resultant PMB could present a further positive effect on the fatigue factor. In terms of the samples that combined plastic and crumb rubber, the improvements in the fatigue resistance can be attributed to the intrinsic properties of the plastomer portion, and better crack resistance due to the crumb rubber portion (Navarro et al., 2009; Yang and Cheng, 2016; Yao et al., 2018). However, it is also important to note that the addition of large quantities of these two elements can considerably increase the viscosity of the binder, and it might provoke the failing of the cracking resistance(Farahani et al., 2017a). Thus, a possible alternative additive is oil, for it could alleviate the workability issue (Maharaj and Maharaj, 2015), and it could also improve the fatigue resistance of the resultant binder(Liu et al., 2018; Yang et al., 2014; Yu et al., 2019).
The fatigue resistance evaluation of the plastic asphalt mix can confirm that the resistance to cracking can indeed be improved after the addition of plastic waste. As the present sample is not big enough to

make a definite conclusion, it seems pertinent to include another analysis that can confirm the benefits of plastic waste on fatigue resistance. To do so, we evaluated some external articles that studied the stiffness on plastic asphalt mixes, instead of PMB. These studies have reported that the addition of plastic waste into the asphalt mix produce positive results in the cracking resistance property (Abdo, 2017; Dehghan and Modarres, 2017; Moghaddam et al., 2012; Ranieri et al., 2017; Sarang et al., 2016). Sarang et al. (2016), for instance, reported that the addition of 8% of plastic waste, PP and PE for this case, enhanced the asphalt mix' fatigue life, and Ranieri et al. (2017), in terms of cracking resistance, suggested that the asphalt mix combined with 5% of HDPE presents a viable alternative to the conventional bitumen.

Low-Temperature crack resistance

For the lower grading in the PG system, the most common methods are the creep stiffness and direct tension tests. In the creep stiffness test, a bending beam rheometer (BBR) is used and two parameters are collected: the creep stiffness (S) and the creep ratio (m-value). The former is the bitumens' resistance to creep loading and the latter is the ability to disperse accumulated stress. Bitumen that is highly resistant to cold temperatures presents low S and high m-value, where the limits for these two properties are a maximum of 300 MPa and a minimum of 0.3 MPa, respectively(AASHTO, 2012). Regarding the direct tension test, it measures the failure strain at different low temperatures, and the bitumen complies with the PG standard if this failure strain is more than 1%. Among the sample, 14 articles employed the BBR while none examined the direct tension. Therefore, the discussion in this section is based on the evaluation of the low-temperature resistance using the BBR. Figure 17 depicts the results of this test on the PG grading.

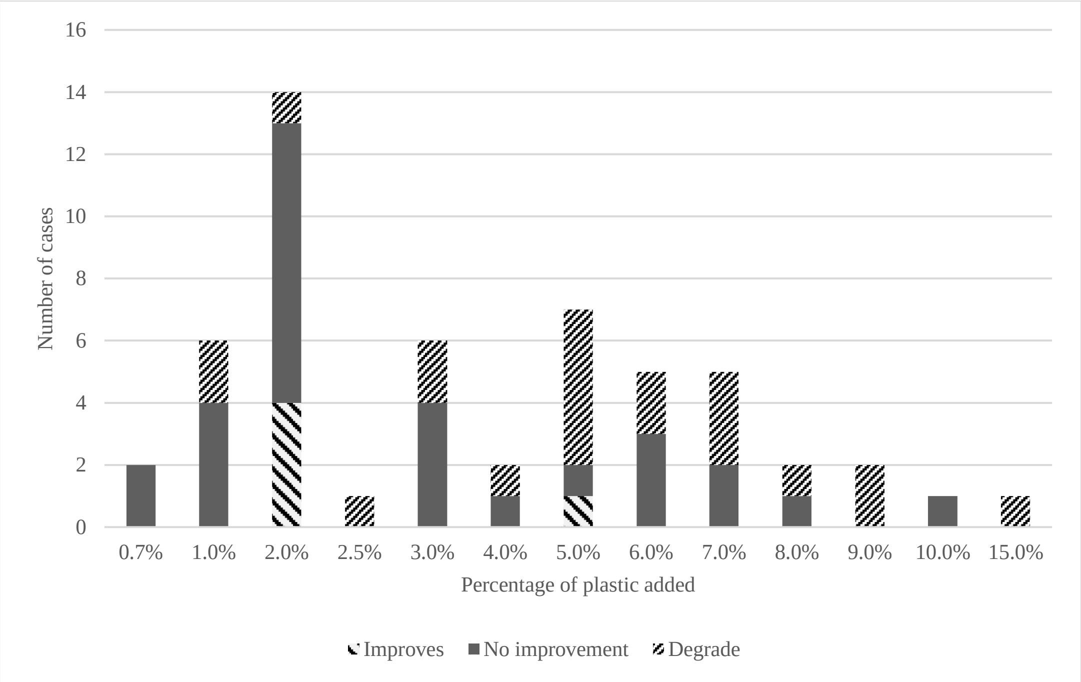


Figure 17 Effects of the addition of plastic waste on the low-temperature resistance grading of bitumen.

Studies showed three possible outcomes in the low-temperature crack resistance: improvement, no-improvement, and degradation. The latter result occurs when instead of becoming more resistant to cold temperatures, the PMB performance worsens and provokes a downgrade in the PG lower limit. None of the samples presented an outcome where the viscosity requisite was violated. However,

sample article did not report on viscosity.
The addition of plastic waste does not improve the cold cracking resistance of the bitumen, and among the limited number of articles that did, no clear reason was found for this. In respect to the improved sample group, only five samples obtained from two articles indicated an upgrade in their cold-temperature grading(Köfteci et al., 2014; Padhan et al., 2018b). The first factor noted in these articles is that they employed small percentages of plastic, and contrary to what happened in the rutting section, it appears that low content of plastic waste can indeed result in an improvement of low-temperature resistance. In terms of plastic-type, Köfteci et al. (2014) employed PVC from three sources (windows, blinds, and cables), and the only sample that presented an upgrade was PVC from window frames at 5%. This result leads to the idea that even plastics of the same type can present different results depending on their specific composition, and that this effect could be strong enough to modify the grading of the bitumen. However, it appears that the PVC would need an additive to present a real effect on the bitumen grading. Padhan et al. (2018b) experimented with a combination of polystyrene (PS), a cross-linking agent, and sulphur based modifier, and showed positive results in all of their samples, demonstrating that the addition of these components not only improve the PMB storage stability, but they also can enhance the PMB's cold cracking resistance. Nevertheless, chemical reactions do not always result in better cold-resistant bitumen, and if future researchers are interested in enhancing the cold resistance, they might need to be cautious about the selection of the chemical agents to use and their nature.
Regarding the sample group that showed no improvements (52% of the total observations), this group contains the three possible plastic additives: untreated plastic, plastic with additional polymer and modified plastic. In terms of untreated plastic, the evaluated types were PVC, LDPE, and PET, and the main reason for no improvement, as Köfteci et al. (2014) stated, is that the addition of these polymers increased the bitumen's stiffness. Thus, it produces a bitumen more susceptible to cold cracking. This result is in agreement with the literature review of Behnood and Gharehveran (2019), where it was identified that the weak resistance of PP, PE, and EVA to cold temperatures was a significant disadvantage of these polymers. In bitumen with an additional polymer, such as crumb rubber and RAP, although they displayed better results than virgin bitumen, in terms of creep stiffness and m-value, their impact was not enough to upgrade the low PG level. A similar trend was also seen in some studies where the plastic was chemically modified. With this in mind, it seems that plastic type and the percentage of addition do not have a significant effect on the cold temperature PG grading, so other factors, such as mixing parameters and bitumen nature, might affect it. Behnood and Gharehveran (2019), for instance, discussed how each type of bitumen reacts differently to the polymer addition in terms of cold resistance, and how soft-graded bitumens are the only binders that present some significant effect after the addition of polymer. Hence, it is plausible to think that the bitumen's nature presents an impact on the cold resistance.

In terms of PG degradation, 39% of the observations found that the addition of plastic downgrades the bitumen's lower PG limit. The untreated plastic types included in this group were HDPE, LDPE, PVC, and high impact polystyrene (HIPS) (Behnood and Gharehveran, 2019), and the only plastic-type with an additional modification was irradiated HDPE(Ahmedzade, P. et al., 2014). Upon close inspection of these results, it is possible to see that no significant relationship between plastic-type and the lower PG limit exists. PVC, for instance, is a plastic type that presented the three possible outcomes: improvement, no improvement, and degraded, and the same was observed in the case of PE, although this one only showed the no improvement and degraded outcome. For this reason, we suspect that the percentage added presents a more direct effect on the cold cracking resistance than the type. However, inspecting Figure 17, the percentage does not seem to have an apparent impact on the property either. Thus, the only explanation that seems logical is that the low cracking resistance depends mainly on the base bitumen and plastic modification, as demonstrated by Teltayev et al. (2019).

To sum up, cold cracking resistance is one of the significant disadvantages of PMB. Among the observations that studied the Superpave property with the BBR, only 9% resulted in an improvement in the grade. This result was expected after observing the response of the PMB in the penetration and softening point properties. These observations prove that the addition of plastic waste increases the stiffness of the bitumen, making it more resistant to permanent deformation but more prone to cracking. Therefore, it can be confirmed again that the best results of the PMB can only be evidenced in hot weathers, and not in cold temperatures.

3.4 Optimal percentage of addition

Based on the studies included in this review, a graph summarising the recommended percentage of plastic addition was prepared. Figure 18 depicts this recommended percentage of plastic addition by plastic-type. It is important to note that these results only include those articles that evaluated the plastic addition, and not those that added chemical reactions or other additives. In average, the content recommended is 4.5%, which confirms that the plastic modified is only feasible when it is added as a modifier and not as a bitumen extender or substitute. It is also possible to see that among the plastic types, PVC is the polymer that permits the highest addition (6.25% on average), while PET presents the lowest one (3.57%).

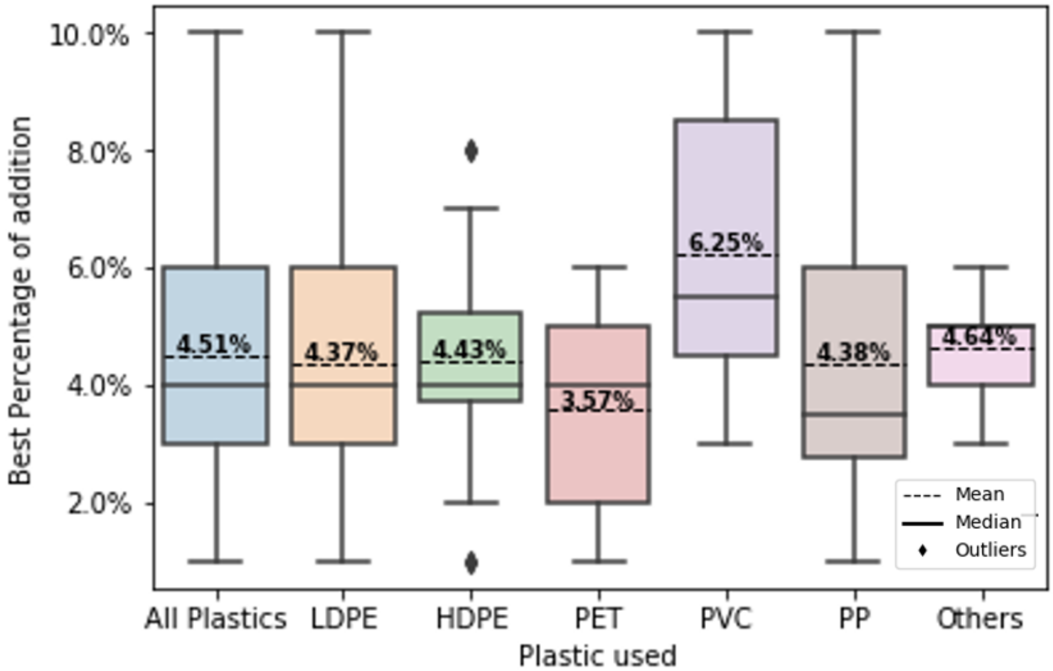


Figure 18 Optimum percentage of plastic addition into the bitumen.

4. Conclusion and further development

The addition of plastic waste to the bitumen to improve its characteristics has been successfully reviewed through a systematic quantitative literature review. There are three possible techniques to add this waste into bitumen: unmodified plastic waste; which represents 83% of the studies; with an additional chemical reaction (11%), and in combination with other materials (51%). Because some articles evaluated more than one pretreatment method, the percentage sum is not 100%. Chemical reactions and the combination of materials have been a significant focus of researchers since 2009 because they could partly alleviate the storage stability and viscosity issues of the plastic modified bitumen. In the present review, this viscosity and storage stability problem has been reported by 32% and 73% of the articles, respectively. Moreover, some researchers have also studied new alternatives to add plastic waste by combining different pretreatment methods and even with new innovative ones, such as pyrolysis and irradiation.

In general, the addition of plastic waste, regardless of the plastic type or pretreatment method, can considerably improve the bitumen's hot temperature resistance, as long as it does not affect the workability properties. This advantage has been supported by measurements of conventional properties, such as penetration and softening point. 98% of the articles that studied the penetration and 94% that did the softening point reported that the addition of plastic waste generates a bitumen modified less susceptible to hot temperature damage. Interestingly, after some comparative studies, researchers have even concluded that plastic waste can become a cheaper alternative to other typical modifiers, such as SBS, if the percentage of addition is significant enough to modify the internal structure of the virgin bitumen. Thus, an improved bitumen could only occur if a correct balance between the percentage of addition and binder properties were optimised. Small quantities will not be enough to improve the binder's resistance to hot temperature, and large percentages, on the other hand, will cause viscosity and storage stability issues. *The present systematic analysis has identified 4.5% as the optimal percentage of plastic waste addition.*

This SQLR also created statistical models for predicting the change of penetration, softening point and viscosity in bitumen that has been modified with plastic waste. The models employed for predicting these conventional properties were shallow artificial neural networks. Because these predictive models presented high accuracy, characterised by R, MSE and MAPE measurements, they can be valuable tools for stakeholders. Researchers or road developers interested in the topic could apply these models for identifying the mixing parameters, the plastic-type and the percentage of addition, that will be required for a desirable plastic modified bitumen.

Superpave properties including rutting resistance, fatigue resistance and cold temperature cracking resistance were also reviewed. The results showed that 75% of the samples that evaluated the hot temperature resistance through the rutting factor presented an improvement in the upper limit of the Superpave grading. Similarly, 47% resulted in an enhancement in the fatigue factor. The only Superpave property that presented negative results was the cold cracking resistance, in which 38% of the samples concluded that the addition of plastic waste deteriorates the lower limit of the Superpave grading.

Last, with these conclusions in mind, we suggest three possible directions for future research: evaluating the economic and environmental efficiency of plastic addition to bitumen; investigating the effect of different plastic pre-treatment method to solve the workability and storage stability issues and the resistance to cold temperature cracking; and comparative performance of plastic modified bitumen with commercial bitumen modifiers.

5. Limitations

The number of samples collected about viscosity values and Superpave properties were limited and in turn, may have affected the accuracy of the statistical models and the results described in the SQLR. In the case of viscosity values, there was a small sample of articles that studied the viscosity at 135°C, and some of them measured this value using methodologies that did not follow the prescribed official regulations, so they were excluded from the study, which resulted in a smaller sample. Another issue is that there was a clear overrepresentation of PP and PE. Also, few articles reported the mixing conditions.

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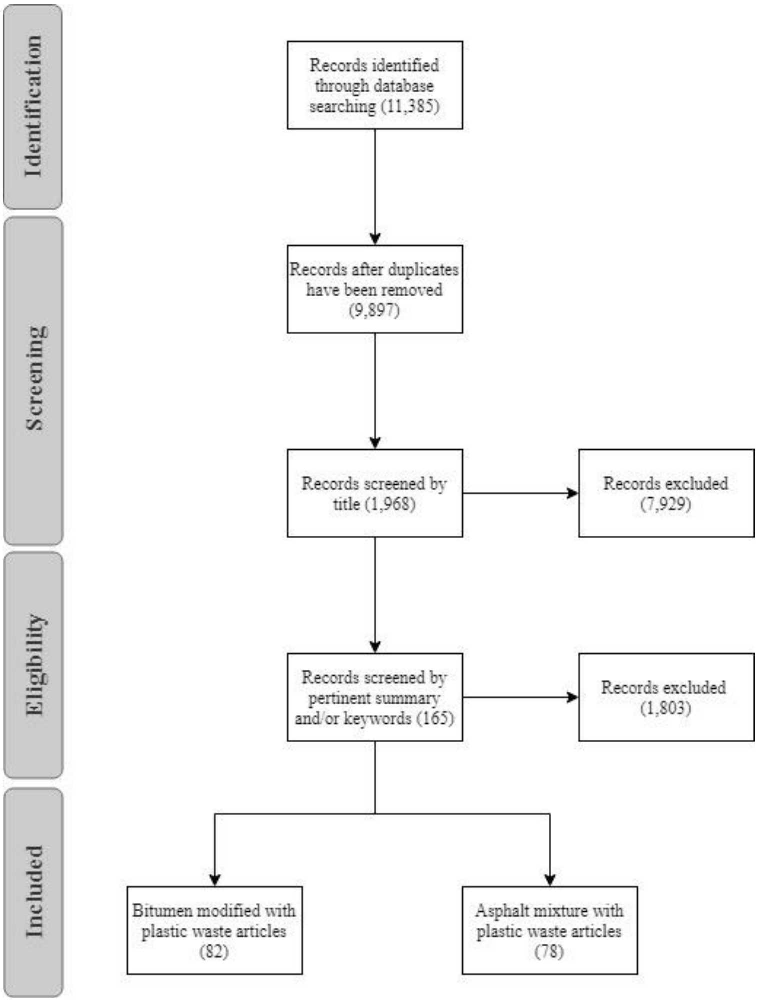
Appendix



Appendix A PRISMA statement.