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Characterization of thermal properties and combustion behaviour of asphalt mixtures in the cone calorimeter

Alice Bonati [a,*], Sara Rainieri [b], Giovanna Bochicchio [c], Barbara Tessadri [c], Felice Giuliani [a]

[a] University of Parma, Department of Civil and Environmental Engineering and Architecture, Parco Area delle Scienze, 181/A, 43124 Parma, Italy
[b] University of Parma, Department of Industrial Engineering, Parco Area delle Scienze, 181/A, 43124 Parma, Italy
[c] National Research Council of Italy (CNR), Trees and Timber Institute-Fire Laboratories, Via Biasi, 75, 38010 San Michele all'Adige, Italy

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ABSTRACT

In case of vehicle fires in highway tunnels, high temperatures, low visibility along with the emission of toxic and dangerous gases represent significant hazards for the safety of the vehicle passengers involved, as well as for the integrity of the tunnel structure. Thus, materials potentially exposed to fires must show adequate fire behaviour in order to guarantee the safety of passengers, rescue teams and structures. The present study addresses the characterization of thermal properties and combustion behaviour of different kinds of asphalt mixtures by means of cone calorimeter tests performed at different radiant heat fluxes. The results highlighted that coarse aggregates of different nature mainly affect the ignition properties of mixtures while the air voids content plays the leading role in governing the overall fire behaviour.

1. Introduction

1.1. General background

The importance of defining adequate instruments for improving tunnel safety has recently become a pressing necessity. Indeed, several fire incidents happened in tunnels in the last decades, thus calling into question the effectiveness of existing safety measurements and highlighting the great relevance of a proper selection of construction materials to achieve reasonable fire safety. In this context, the European Union Directive 2004/54/EC [1] and the work of the World Road Association [2] actually represent useful guidelines on minimum safety requirements for tunnels and fire prevention tools. Nevertheless, a specific research aimed at defining road materials with appropriate fire reaction has been carried out only in the last years [3,4]. Generally, road pavements can be realized with two different kinds of materials: asphalt mixture or cement concrete. Essentially, asphalt is a mixture of natural raw materials: coarse and fine aggregates, filler and asphalt binder. In this field, the most traditional technical solution is Hot Mix Asphalt (HMA), representing a mixture of approximately 95% of well graded aggregates, together with filler, while asphalt binder represents the remaining 5% of the mixture. Asphalt binder is the black component that "glues" the aggregates together and it is derived as a residual product from the refining crude oil. Filler is composed of particles smallest than 0.075 mm and is used in asphalt to fill the smallest voids and stabilize the binder at high temperatures. Coarse and fine aggregates are chosen in order to reproduce a specific aggregate gradation which provides a solid skeleton to the mixture. Depending on the selected aggregate distribution, completely different structures can be achieved, especially in terms of air voids content. Generally, mixtures characterized by high air voids content (greater than 20%) are referred to as "open graded" mixtures while "dense graded" mixture are characterized by low air voids content, typically around 5%. In highway tunnels, dense graded mixtures are generally preferred due to negligible drainage requirement. Moreover, open graded mixtures are not advised because of their open and permeable character, which could promote the spread of fire in case of accidents involving flammable liquids.

In a few European countries, Portland cement concrete pavements are exclusively admitted in tunnels thanks to its incombustible nature. Nonetheless, in case of fires they are susceptible to relevant spalling phenomena which lead to significant and expensive operations of rehabilitation. On the other hand, asphalt mixtures show advantages in terms of functional characteristics but they were found to be ignitable [5] when subjected to remarkable irradiances, potentially achievable in case of heavy goods vehicle fires in tunnels [6]. Therefore, several studies focused on the improvement of the fire behaviour of asphalt binders by the addition of Flame Retardant additives (FRs) derived from polymer technology.

* Corresponding author. Fax: +39 0521 905924.
E-mail address: alice.bonati@nemo.unipr.it (A. Bonati).

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First investigations were based on halogenated FRs [7,8] which operate in the gas phase, by replacing the free radicals responsible for flame propagation with more stable species, such as chlorine and bromine anions, able to stop the combustion reaction. Substantial enhancement in terms of asphalt binders' flammability was achieved but some important drawbacks, such as the formation of smoky, toxic and corrosive effluents, addressed the research to alternative “halogen-free” FRs, i.e. metal hydroxides, carbonates, and phosphorus compounds. More specifically, alkaline hydroxide fillers resulted capable of improving asphalt binders ignitability and thermal stability [9,10]. In particular, aluminium hydroxide (also referred to as alumina trihydrate) and magnesium hydroxide were found to be the most suitable additives for asphalt mastics thanks to their capacity in delaying the asphalt binder pyrolysis through a “heat sink” mechanism. Further details concerning the fire retardant mechanisms of such fillers can also be found in Refs. [11,12]. It is worth noting that all the above-mentioned experiences focused on the fire behaviour of asphalt binders by means of thermogravimetric analysis (TGA) and Limiting Oxygen Index (LOI) tests, thus excluding the influence of mineral aggregates.

First experimental investigation on the fire behaviour of asphalt mixtures was carried out by Noumowe [13] and highlighted the ignition of asphalt mixes between 480 °C and 530 °C, when subjected to the ISO 834 temperature curve. Further attempts of investigating the reaction to fire of asphalt pavements were performed [4] and outlined the impossibility of applying the criteria specified in EN 13501-1 [14] for the classification of asphalt floorings. Indeed, the critical heat flux required for sustained flaming was significantly higher than that generated in the test, approximately equal to 12 kW m^{-2}, thus making the radiant panel flooring test [15] unsuitable for the classification of asphalt pavements.

Cone calorimeter test was found an effective method for assessing material flammability and specific ignition conditions. During the test, several fire properties can be measured, thus allowing a comparison among different materials in terms of fire hazards. Further details concerning this kind of apparatus can be extensively found in literature [16–18]. Testing asphalt mixtures with cone calorimeter was successfully performed in different experiences [3–5] following the ISO 5660-1 specifications [19]. Colwell showed that asphalt mixtures could ignite when subjected to heat fluxes higher than 30 kW m^{-2} [4]. Anyway, the fire behaviour can be dramatically influenced by the asphalt binder content, the aggregate gradation and the presence of specific flame retardant fillers [3,5,20,21], thus indicating the need of specific mix design criteria to achieve a suitable fire reaction.

1.2. Research objectives

The main purpose of the present investigation was the evaluation of the basic fire properties of conventional dense and open graded asphalt mixtures characterized by different aggregate gradation and air voids content. To this aim, cone calorimeter tests were performed at three distinct radiant heat fluxes (35, 50 and 70 kW m^{-2}) in order to identify the critical heat flux for both the analysed mixes, along with their heat release rate and smoke production rate. The influence of coarse aggregates on the thermal properties of mixtures was also assessed by testing in a specific cone calorimeter configuration (70 kW m^{-2} irradiance level) three different mixtures characterised by the same air voids and asphalt binder contents but with aggregates composed of crushed porphyry, electric arc furnace (EAF) steel slag and light expanded clay aggregates (LECA) respectively. Finally, basic ignitability parameters for conventional dense graded mixture were derived by means of the pure conduction model for ignition.

2. Experimental programme

2.1. Materials

Asphalt mixtures were produced using a 50/70 penetration grade neat asphalt binder characterized by softening point of 52 °C (ASTM D36-12, [22]) and penetration equal to 44 dmm (ASTM D5-06, [23]). Conventional limestone filler (100% passing at 0.063 mm sieve) is characterised by a specific gravity of 2.71 g cm^{-3}, bulk density equal to 600 kg m^{-3} and median (d_{50}) particle size of 3.2 μm. The main chemical component (99 wt%) of filler was calcium carbonate.

Two different aggregate gradations were considered in order to compare the behaviour of conventional dense and open graded mixtures. The particle size range of both the gradations was defined according to the Italian specifications [24] and the corresponding aggregate grading curves are depicted in Fig. 1.

Three different dense graded mixtures were produced with the aim to highlight the influence of aggregates on the fire behaviour of asphalt mixtures. Limestone 0–4 mm fraction was combined with the 4–16 mm fraction composed of porphyry, EAF steel slag, and LECA respectively. The specific gravity of porphyry, EAF, and LECA were respectively equal to 2.58, 3.92, and 1.13 g cm^{-3}. The thermal conductivity of LECA aggregates provided by the supplier was equal to 0.13 Wm^{-1} K^{-1}. No technical data were available for the EAF aggregates while for porphyry aggregates an average thermal conductivity value of 2.80 Wm^{-1} K^{-1} could be derived from literature [25].

Open graded mixture was produced with the following fractions: 0–4 mm limestone and 4–20 mm crushed porphyry; in this case, only natural aggregates were used in order to focus the attention on the aggregate gradation.

The asphalt binder was kept constant for all the asphalt mixtures produced and equal to 5.5 wt% referred to the weight of mineral aggregates. This strategy allowed to investigate the effect of the structure of the mixtures and not of the content of the combustible portion on the material's fire behaviour. The limestone filler content was chosen in order to obtain asphalt mastics characterized by bitumen to filler ratio equal to 1/1 (wt/wt).

Table 1 synthetically describes the resulting mixtures along with their main physical properties. Theoretical maximum specific gravity (G_{mm}) was determined for each asphalt mixture according to ASTM D6857-09 [26].

For each asphalt mixture, three 100 mm diameter cylindrical samples were prepared by using a Superpave gyratory shear compaction technique, with a vertical pressure of 600 kPa and setting the compaction level to 100 gyrations, which is the recommended N_{des} for traffic within the range 10–30 MESALs.

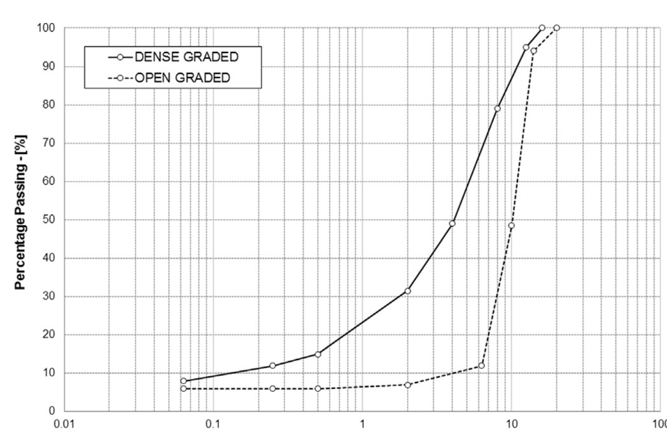

Fig. 1. Aggregate grading curves for dense and open graded mixtures.