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Review

Carbon black vs. black carbon and other airborne materials containing elemental carbon: Physical and chemical distinctions☆

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ABSTRACT

Airborne particles containing elemental carbon (EC) are currently at the forefront of scientific and regulatory scrutiny, including black carbon, carbon black, and engineered carbon-based nanomaterials, e.g., carbon nanotubes, fullerenes, and graphene. Scientists and regulators sometimes group these EC-containing particles together, for example, interchangeably using the terms carbon black and black carbon despite one being a manufactured product with well-controlled properties and the other being an undesired, incomplete-combustion byproduct with diverse properties. In this critical review, we synthesize information on the contrasting properties of EC-containing particles in order to highlight significant differences that can affect hazard potential. We demonstrate why carbon black should not be considered a model particle representative of either combustion soots or engineered carbon-based nanomaterials. Overall, scientific studies need to distinguish these highly different EC-containing particles with care and precision so as to forestall unwarranted extrapolation of properties, hazard potential, and study conclusions from one material to another.

1. Introduction

Carbon black (CB) is a manufactured product that has been in commerce for over a century. Consisting of a fine black powder of nearly pure elemental carbon (EC), it has numerous applications in a variety of commercial and consumer products. Its single largest use is as a reinforcing agent in vehicle tires and rubber automotive products, while other common, everyday products that often contain CB include inks, paints, plastics, and coatings. It is manufactured by either partial combustion or thermal decomposition of gaseous or liquid hydrocarbons under controlled conditions optimized to yield a variety of CB grades having specified ranges of properties (e.g., specific surface area, particle size and structure, conductivity, and color).

As discussed in a previous paper (Watson and Valberg, 2001), the terms carbon black and soot have often been used interchangeably despite the fact that soot by definition is an undesired byproduct of incomplete combustion of fossil fuels and biomass. Watson and Valberg (2001) demonstrated that CB and soot are physically and chemically distinct substances. CB is simply a quasi-graphitic form of nearly pure EC that is distinguished by its very low quantities of extractable organic compounds and total inorganics (generally <1% of each; IARC, 2010; McCunney et al., 2012; OECD, 2005; Wang et al., 2003; Watson and Valberg, 2001). In addition, CB has a characteristic particle morphology that consists of aciniform (grape-like) aggregates of highly fused spherical primary particles, with the aggregates clustered into larger-sized agglomerates. In stark contrast, combustion soot is a highly heterogeneous substance that generally includes a major organic carbon fraction (oftentimes >50% of total mass) and significantly higher ash and extractable organic matter contents than carbon black. Its chemical and physical properties are highly variable depending on its source. As described previously by Watson and Valberg (2001), some soot forms such as diesel exhaust particulate (DEP) can have morphologies resembling the aciniform aggregates of carbon black, while other soots can exhibit significant variations in morphology.

Since the publication of the Watson and Valberg paper in 2001, there has been continued misuse of soot as a synonym for carbon black. In fact, the US National Library of Medicine's PubMed biomedical literature database uses soot as a MeSH (Medical Subject Headings) indexing term for carbon black. Adding to these errors in nomenclature, the term black carbon has gained widespread usage in recent years to describe light-absorbing carbonaceous aerosols that are now recognized as key climate-forcing agents (Andreae and

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Gelencsér, 2006). More specifically, black carbon has emerged as the leading term among climate modelers to describe the fraction of combustion-related carbonaceous aerosols that are strongly light-adsorbing (Bond and Bergstrom, 2005). Other terms like soot, elemental carbon, and graphitic carbon continue to be used synonymously with black carbon, although there are efforts to develop more precise nomenclature that distinguishes between these terms based on measurement techniques and light-absorbing properties (Andreae and Gelencsér, 2006; Bond and Bergstrom, 2005; Kupiainen and Klimont, 2004; US EPA, 2012). We will not enter this nomenclature debate, and for the purposes of this paper which is focused on differentiating CB from other airborne EC-containing materials, we will use the term black carbon (BC) particles as referring to EC-containing fine particles that are commonly found in ambient air due to emissions from incomplete combustion of fossil fuels and biomass. We will use the term black carbon rather than soot since there are other soot components that have little, if any, EC content; these include chars, coke-oven emissions, as well as a class of organic carbon-based particles, known as "Brown Carbon (BrC)", that have received a great deal of recent research attention due to their light-absorbing properties (Andreae and Gelencsér, 2006; Kuhlbusch et al., 2009; US EPA, 2012). Termed brown carbon to reflect their characteristic brown appearance, BrC particles are found in the combustion soot of biomass and biofuels, and contain little, if any, elemental or black carbon (Andreae and Gelencsér, 2006; Chakrabarty et al., 2010).

Given the similarity in their names, it is not surprising that the terms carbon black and black carbon are often misused. Examples of the misuse of these terms are widespread in the scientific literature, including even in the March 2012 US Environmental Protection Agency (US EPA, 2012) Report to Congress on Black Carbon. Specifically, in Chapter 3 of this report that addresses black carbon effects on public health and the environment, US EPA referred to several studies (Tankersley et al., 2004, 2007, 2008) where laboratory animals were exposed to carbon black as providing evidence of the potential health effects of black carbon (BC). Confusing carbon black with black carbon, Büchner et al. (2013) repeatedly referred to ultrafine carbon black particles as being "one of the major constituents of air pollution", stating that carbon black particles are "one of the major constituents of industrial and exhaust emissions" and that they are "produced not only by traffic and industry, but also in every household and office". Similarly, Reisetter et al. (2011) referred to carbon black particles as being "found in many different environmental exposures" and as "a primary component in ambient pollution and diesel exhaust". In a letter to the editor regarding the Reisetter et al. (2011) publication, Levy et al. (2011) clarified that these references would be more accurate for black carbon particles. As explained by Levy et al. (2011), unbound CB particles are not generally released into the environment from CB products like tires and other rubber products since they are tightly bound in product matrices. Other papers like Garza et al. (2008) and Murr (2008) have referred to "commercial black carbon", which would appear to be a misnomer for "commercial carbon black" given that they refer to it as being a constituent of tires. To our knowledge, black carbon is not produced commercially.

Due to the continued misuse of soot and now black carbon as synonyms for carbon black (and vice versa), it is appropriate to update the Watson and Valberg (2001) analysis. Since the publication of this paper over ten years ago, there has emerged a greater understanding of the physical and chemical properties of the various forms of combustion-derived black carbon particles. This knowledge base has been improved as a result of the heightened efforts of researchers and regulators to better understand the climate-forcing properties and adverse health effects of black carbon (Janssen et al., 2011, 2012; UNEP, 2011; US EPA, 2012). In addition, with the commercial development of several kinds of engineered carbon-based nanomaterials (e.g., fullerenes, single-walled and multi-walled carbon nanotubes, graphene) and the laboratory generation of ultrafine elemental carbon particles for toxicological study (e.g., spark-generated elemental carbon, SGEC; diffusion flame particles, DFP), the spectrum of carbonaceous particles is now broader than it was ten years ago. Since carbon black has gained usage as a test particle in numerous toxicology studies of various engineered nanomaterials including carbon nanotubes and fullerenes, there is a particular need to distinguish carbon black from engineered carbon-based nanomaterials. Focusing on physical and chemical characteristics, we thus examine how CB differs from black carbon and other EC-containing particles that might become airborne.

2. Overview of different airborne EC-containing materials

Table 1 summarizes some of the general differences between CB and other classes of airborne EC-containing materials. Below, we provide brief descriptions of each particle type, focusing in particular on their origins and sources and how we may come into contact with them. In subsequent sections, we focus on the physical and chemical properties of CB and contrast them to those of other airborne EC-containing materials.

2.1. Carbon black

CB is the name of a group of manufactured fine-particle products that have a variety of different trade names and physicochemical properties, but share a chemical composition of nearly pure EC. CB has been commercially produced for over 100 years, and with 2008 worldwide production totaling approximately 9.8 million metric tonnes, it has been cited as one of the top 50 industrial chemicals manufactured worldwide (ICBA, 2004; McCunney et al., 2012). Rubber applications – tire-related automotive uses (tires, tubes, tread), rubber automotive products (e.g., belts, hoses, miscellaneous), and non-automotive industrial rubber products including industrial molded and extruded products – dominate worldwide CB use patterns, consuming approximately 90% of CB used in the US, Western Europe, and Japan (IARC, 2010; McCunney et al., 2012). The remaining 10% is divided among other special CB applications that include uses as a pigment, UV absorbing, and/or conducting agent in inks, coatings, and plastics (IARC, 2010; ICBA, 2004; McCunney et al., 2012; Wang et al., 2003).

The greatest potential for CB exposure is in CB manufacturing and its production, collection, and handling (IARC, 2010; McCunney et al., 2012). While CB continues to be manufactured via several well-established manufacturing processes (the oil furnace process, the thermal black process, the acetylene black process, the lamp black process, the channel black process, and the gas black process; for descriptions of each process, see McCunney et al., 2012; Wang et al., 2003), greater than 95% of both US and worldwide carbon black production is generated via the oil furnace process (IARC, 2010; McCunney et al., 2012; Wang et al., 2003). In the oil furnace process, heavy aromatic petroleum oils are pyrolyzed at extremely high temperatures (1400–1800 °C) to produce CB particles and tail gas (e.g., carbon monoxide, hydrogen, steam). As a continuous process that is conducted within a closed reactor, manufacturing conditions can be carefully controlled in the oil furnace process, such that a variety of carbon black grades with differing properties (e.g., surface area, aggregate size, structure, abrasion resistance, tint strength, etc.) can be produced. As discussed more later, furnace blacks and other carbon black products generally exist as complex particle aggregates and agglomerates in finished products rather than as free individual particles.