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交通活动对公路两侧土壤和灰尘中重金属含量的影响

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摘要:为了解公路交通带来的重金属污染及其在公路两侧土壤中的分布规律,对相关研究结果的分析表明,含铅汽油、润滑油的燃烧,汽车轮胎、刹车里衬的机械磨损等是公路两侧土壤和灰尘中重金属污染的重要来源. 机动车辆排放的含重金属颗粒物或直接沉积在路面灰尘中,或通过干湿沉降沉积在公路两侧的土壤中,使得公路两侧土壤和灰尘中重金属出现不同程度的积累. 一般地,公路两侧土壤中重金属含量随着距公路距离的增加呈指数形式下降. 公路两侧土壤中重金属的含量及其分布格局因受交通流量、车辆类型、地形与路况、绿化带配置和风、降雨等气象条件的影响而异.

关键词:机动车;重金属;公路灰尘;公路两侧土壤

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Effect of road traffic on heavy metals in road dusts and roadside soils

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Abstract: In order to gain an understanding of the concentrations and dispersion patterns of heavy metals emitted by motor vehicles and deposited in road and roadside soils, the concentrations and dispersion patterns of heavy metals were analyzed based on previous studies from different cities at home and abroad. Vehicular emissions, especially combustion of lubricants and lead-gasoline, mechanical abrasion of vehicle tyres and brakes, are the major source of heavy metals such as Pb, Zn, Cu and Cd in road dusts and roadside soils. Particulates containing heavy metals may deposit in road dusts directly or in roadside soils via aerial deposition, which brings about the accumulation of heavy metals in road dusts and roadside soils. Numerous studies have indicated that heavy metals such as Pb, Cu, Zn and Cd have accumulated in road dusts and roadside soils of China and some other countries, which may cause adverse effects on human health and environmental quality. Generally, the concentrations of heavy metals in roadside soils decrease exponentially with increasing distance from the road edge. Dispersion patterns of heavy metal contents vary greatly in different regions, and the differences are attributed mainly to the effects of traffic intensity, topographic profiles (up-down hill), road surface and greenbelts in local region, in addition to micro-meteorological factors, such as wind power and speed, direction of dominant winds and rainfall.

Keywords: motor vehicles; heavy metal; road dusts; roadside soils

1 引言(Introduction)

随着我国汽车工业和交通运输的发展,特别是高速公路的相继运营,公路交通对我国的经济发展起着十分重要的作用. 但是,公路交通的快速发展也带来一系列重金属污染问题,尤其是目前汽车排放性能不佳,车辆维护保养差,车辆平均排放因子较高,使得重金属污染问题更加突出.

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机动车辆直接排放的颗粒物及车辆行驶引起的二次扬尘,是大气粉尘中 Pb、Zn、Cu和 Cd含量升高的重要影响因素 (Kemp, 2002; 韩东昱等, 2004),同时也是公路灰尘和土壤中重金属含量增加的重要因素 (Harrison *et al*, 2003). 含铅汽油中通常含有四乙基铅或四甲基铅等抗爆剂,经燃烧后,烷基铅化合物转化为 PbO 和 PbO_2,继而转化为挥发性的 $PbCl_2$、$PbBr_2$ 和 PbClBr,最后随尾气排出 (Hamamci *et al*, 1997). 据估计,75%的 Pb以颗粒态的形式随汽车尾气进入环境 (Hewitt *et al*, 1990). 汽车轮胎中通常含有二乙基锌盐或二甲基锌盐等抗氧化剂 (Alloway *et al*, 1990),润滑油中通常含有二硫代磷酸锌盐等抗氧化剂及分散剂 (De Miguel *et al*, 1997),镉盐主要作为含锌添加剂的杂质存在于汽车轮胎和润滑油中 (Lagerwerff *et al*, 1970). 因此,汽车轮胎磨损及润滑油燃烧是公路 Zn和 Cd污染的主要来源 (Ellis *et al*, 1982; Sawyer *et al*, 2000). 此外,防腐镀锌汽车板的广泛使用所产生的大量含锌粉尘,也是公路 Zn污染的来源之一. 刹车里衬的磨损不仅造成公路 Cd和 Pb污染 (Johansson *et al*, 2001; Weckwerth, 2001),而且会导致 Cu污染 (Harrison *et al*, 2003; Sternbeck *et al*, 2002; Weckwerth, 2001).

美国 EPA筛选出来自交通污染的 21种主要有毒有害物质,其中包括 Pb、Cu、Zn和 Cd (US Government, 2001). 这些污染物在环境中的积累具有重要的环境指示意义. 因此,深入了解和掌握公路交通造成的公路灰尘和两侧土壤中 Pb、Cu、Zn和 Cd的污染问题,分析 Pb、Cu、Zn和 Cd在公路两侧土壤中的分布格局,为我国公路的规划建设、公路沿线的农业生产布局及公路交通导致的重金属污染的防治提供科学依据.

2 交通对公路灰尘及土壤重金属含量的影响 (Contamination of heavy metals emitted from motor vehicles in road dust and roadside soil)

含铅汽油、润滑油燃烧后的废气排放,车辆轮胎、刹车里衬的机械磨损是公路沿线重金属颗粒物的重要来源. 这些含重金属的颗粒物,一部分直接沉积在路面,一部分飘散在空气中或通过干湿沉降沉积到公路两侧土壤中,对公路灰尘和两侧土壤造成一定程度的重金属污染.

2.1 交通对公路灰尘中重金属含量的影响

公路灰尘对大气中颗粒态 Pb和其他重金属具有吸附作用 (Al-Chalabi *et al*, 1997). 研究发现, Pb、Zn、Cu和 Cd在公路灰尘中已有不同程度的积累 (表 1). Charlesworth等 (2003)发现,伯明翰 (人口数 23万)城市道路灰尘中 Pb、Zn、Cu和 Cd的平均含量均高于考文垂 (人口数 3万)道路灰尘中的含量,尤其是公路十字路口处灰尘中重金属含量较高 (图 1). 1991年,张毅的研究发现,北京北郊安立公路灰尘中 Pb含量分别是北郊土壤中 Pb背景值和

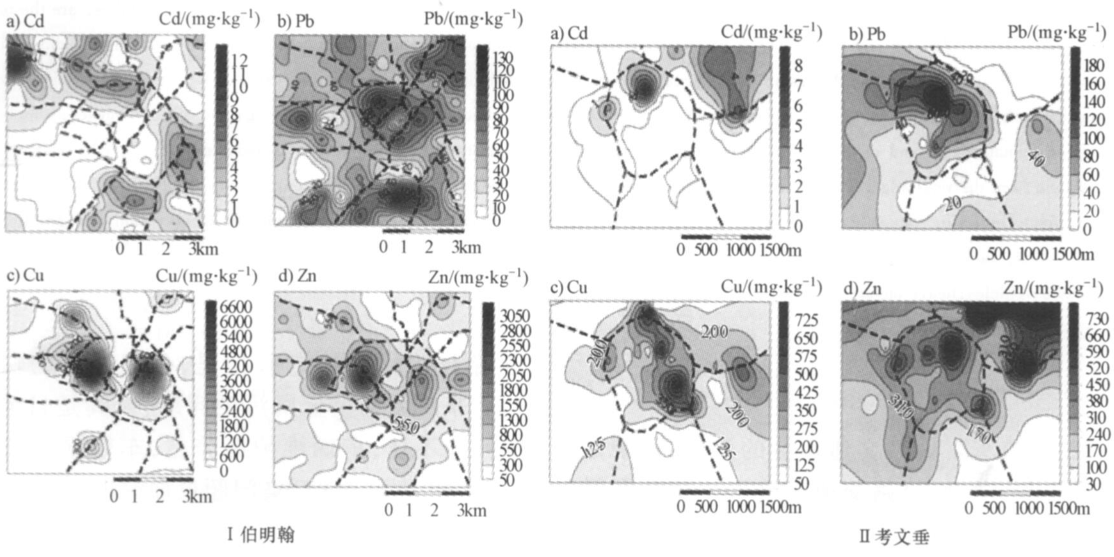


图 1 英国不同城市道路灰尘中重金属的空间分布 (资料来源: Charlesworth *et al*, 2003) (注:图中虚线表示伯明翰和考文垂的主要公路路线)

Fig. 1 Spatial distribution of heavy metals in road dusts in Birmingham and Coventry

表 1 国内外不同城市公路灰尘和土壤中 Pb、Cu、Zn和 Cd的含量

Table 1 Concentration of Pb, Cu, Zn and Cd in road dust and roadside soils of China and some other countries

	城市	样本数	重金属含量 / (mg·kg^{-1}) Pb M ±SD	Pb 背景土壤	Cu M ±SD	Cu 背景土壤	Zn M ±SD	Zn 背景土壤	Cd M ±SD	Cd 背景土壤
灰尘	香港 (Li *et al*, 2001)	45	181 ±92.9	-	173 ±2.25	-	1450 ±869	-	3.77 ±2.25	-
灰尘	香港 (Chan *et al*, 2001)	8	120 ±4	-	110 ±4	-	3840 ±70	-	-	-
灰尘	香港 (Lee *et al*, 2006)	633	214.3 ±147.9	-	445.6 ±708.6	-	2665.0 ±1815.0	-	4.3 ±3.3	-
灰尘	西安 (Han *et al*, 2006)	65	230.5 ±431.0	26	95.0 ±130.2	22.6	421.5 ±456.0	74.2	-	-
灰尘	大田 (Kim *et al*, 1998)	31	52	28	57	24	214	107	-	-
灰尘	马德里 (De Miguel *et al*, 1997)	16	1927 ±3.79	-	188 ±7.83	-	476 ±15.87	-	-	-
灰尘	伦敦 (Warren *et al*, 1987)	12	3495.6	1526.0	513.6	274.4	950.0	600.3	3.75	2.9
灰尘	渥太华 (Rasmussen *et al*, 2001)	45	39.05	-	65.84	-	112.5	-	0.37	-
灰尘	奥斯陆 (De Miguel *et al*, 1997)	16	180 ±12.86	-	123 ±9.46	-	412 ±6.75	-	1.4 ±7.0	-
灰尘	英国考文垂 (Charlesworth *et al*, 2003)	49	47.1 ±5.61	-	226.4 ±8.81	-	385.7 ±6.32	-	0.9 ±3.33	-
灰尘	英国伯明翰 (Charlesworth *et al*, 2003)	100	48.0 ±2.9	-	466.9 ±4.73	-	534 ±11.38	-	1.62 ±7.04	-
灰尘	安曼 (Jiries *et al*, 2001)	8(车流量小)	421.7 ±285.7	-	117 ±28.38	-	-	-	8.6 ±9.5	-
灰尘	安曼 (Jiries *et al*, 2001)	8(车流量大)	642.3 ±493.0	-	167.3 ±56.1	-	-	-	9.37 ±7.73	-
土壤	南京市 (Lu *et al*, 2003)	21	151.4 ±68.2	24.8	117.3 ±83.4	32.2	280.3 ±194.3	78.6	-	-
土壤	香港 (Li *et al*, 2004)	58	94.6 ±61.0	50	23.3 ±23.4	10	125 ±89.1	50	0.62 ±0.82	0.8
土壤	香港 (Lee *et al*, 2006)	236	88.1 ±62.0	-	16.2 ±22.6	-	103 ±91.3	-	0.36 ±0.16	-
土壤	Torino (Biasioli *et al*, 2006)	70	149 ±120.6	20	90 ±47.9	28	183 ±97.3	62	-	-
土壤	瑞典斯德哥尔摩 (Linde *et al*, 2001)	7	100		27		126		0.37	
土壤	塞维利亚 (Ruiz-Cortés *et al*, 2005)	12	92.1		38.4		91.4		2.37	
土壤	尼日利亚 (Ideriah *et al*, 2004)	车流量小	18.96 ±4.11	4.0 ±3.22	11.97 ±2.48	3.34 ±1.25	27.87 ±13.37	14.05 ±6.03	-	-
土壤	尼日利亚 (Ideriah *et al*, 2004)	车流量大	60.63 ±29.58	4.0 ±3.22	37.23 ±15.88	3.34 ±1.25	40.10 ±15.86	14.05 ±6.03	-	-
土壤	约旦安曼 (Jaradan *et al*, 1999)	35 (东侧 1.5m)	188.8 ±71.2	-	29.7 ±7.2	-	121.7 ±13.8	-	0.75 ±0.32	-
土壤	约旦安曼 (Jaradan *et al*, 1999)	35 (西侧 1.5m)	61.5 ±5.6	-	22.5 ±10.3	-	75 ±17.2	-	0.55 ±0.23	-
土壤	美国德克萨斯州 (Turer *et al*, 2003)	22 (车流量大)	720	-	93	-	260	-	-	-
土壤	美国德克萨斯州 (Turer *et al*, 2003)	22 (车流量小)	340	-	71	-	360	-	-	-

公路两侧土壤中 Pb含量的 12.0倍和 5.7倍,这表明公路交通导致公路灰尘中重金属的累积,对公路周边环境造成严重的污染 (张毅, 1991).

2.2 交通对公路两侧土壤中重金属含量的影响

大量研究发现国内外城市公路旁土壤中重金属已出现不同程度的累积 (表 1). 尽管使用无铅汽油后,上海市汽车尾气对大气中 Pb颗粒物的贡献率仅为 20% (Zheng *et al*, 2004);长春市 TSP中 Pb含量比使用含铅汽油时下降约 44%～48% (王晓冬等, 2003). 但重金属在土壤中具有累积特性 (Kelly *et al*, 1996),公路交通造成的土壤重金属污染仍会在相当一段时间内持续下去. 对北京市不同土地利用方式下土壤重金属的研究发现,公路附近的绿化地土壤中 Pb含量达 34.8 $mg\cdot kg^{-1}$,显著高于北京市土壤 Pb背景值 24.6 $mg\cdot kg^{-1}$ ($p<0.05$) (陈同斌等, 2004),公路两侧土壤仍受到交通污染的影响 (郑袁明等, 2005). 北京市旧城区 (市中心)公园表层 (0～5 cm)土壤中 Pb、Cu和 Zn均超过北京市土壤背景值 (陈同斌等, 2004), Cu和 Pb含量明显高于旧城区外公园土壤的含量,这与旧城区交通密度大、人类活动频繁等有关 (Chen *et al*, 2005).

3 影响公路两侧土壤中重金属含量及分布的因素 (Factors affecting heavy metals in roadside soils)

公路两侧土壤中重金属含量及其分布格局除受土壤母质的影响外,主要受交通流量 (Garcia *et al*, 1998)、车辆类型 (Legret *et al*, 1999)、地形与路面状况 (Othman *et al*, 1997)、绿化带配置 (Chan *et al*, 1997)等交通状况,当地风力、风速、盛行风向、降雨量和径流量 (Othman *et al*, 1997; Piron-Frenet *et al*, 1994; Wróbel *et al*, 1999)等气候气象条件的影响.

3.1 交通流量

交通流量是影响公路两侧土壤中重金属含量及其分布的主要影响因素之一 (Garcia *et al*, 1998; Ozkan *et al*, 2005). Ideriah等研究发现,公路日车流量与该公路两侧土壤中 Pb含量呈正相关关系 ($r=0.916$, $n=17$);车流量大 ($>2\times10^6$辆 $\cdot d^{-1}$)与车流量小 ($<2\times10^6$ 辆 $\cdot d^{-1}$)的不同公路两侧,土壤中 Pb含量存在显著性差异 ($p<0.05$) (Ideriah *et al*, 2004). 香港城市土壤中 Pb的平均含量是交通流量相对较小的深圳土壤的 1.45倍 (Chen *et al*, 1997). 尼日利亚拉各斯某公路两侧土壤中 Pb含量与交通流量 (车流量为 10万辆 $\cdot d^{-1}$)呈显著正相关关系 ($r=0.74$, $n=16$),公路灰尘中 Pb和 Zn含量均高于车流量为 3.4万辆 $\cdot d^{-1}$的贝尼奥尼沙公路 (图 2) (Ogunsola *et al*, 1994).

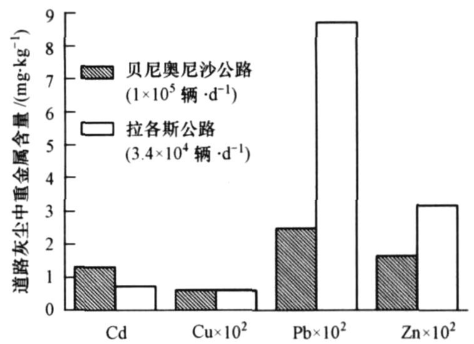


图 2 不同车流量公路灰尘中 Cd、Cu、Pb和 Zn的含量 (根据 Ogunsola *et al*., 1994的数据重新做图)

Fig. 2 Concentration of Cd, Cu, Pb and Zn in road dust from roads with different vehicle densities

3.2 地形及路况

公路所处的地理位置直接影响公路两侧土壤中重金属的含量及其分布格局. 山区和丘陵地带,空气流动不畅,机动车辆排放的重金属颗粒物被大气稀释的空间受限,容易滞留在公路附近;平坦地形有利于重金属颗粒物的扩散、稀释,却容易造成大范围的污染.

十字路口、盘旋路和路况较差的公路,由于车流量大、车辆行驶缓慢、刹车现象频繁、尾气排放加重、轮胎磨损严重,从而产生大量含 Pb、Zn、Cu和 Cd的颗粒物,造成严重的重金属污染. 而绿化带可以通过滞留、吸附和过滤等方式净化空气,有效阻止重金属颗粒物的进一步扩散,对公路两侧土壤的重金属污染有很好的防治作用 (Chan *et al*, 1997). 资料表明,高 6 m、宽 10 m或高 12 m、宽 25 m的绿化带可使大气颗粒物分别降低 65%或 75%,从而使进入公路两侧土壤中的重金属含量降低 (邹良东等, 1996). 阮宏华等发现,公路两侧林地土壤中 Pb含量在路边 5 m处较高,在距公路 5～100 m Pb含量较低 (阮宏华等, 1999). 徐永荣等发现,绿化带使公路两侧重金属峰值的出现点距公路的距离缩短,并且有效降低重金属污染程度,其峰值降低 25%～50% (徐永荣等, 2002).

3.3 气候与气象因素

受风的影响,机动车辆产生的含重金属的颗粒物容易扩散到周边环境 (Lee *et al*, 2006). 风向会影响公路两侧土壤中重金属的含量,下风向地区土壤中重金属的平均含量比上风向地区高 (Viard *et al*, 2004). 风速和风力较大的地区,重金属颗粒物一方面能够得到有效稀释,另一方面却形成较大

范围的污染.

降雨量对公路灰尘和土壤中重金属含量的影响较大.当累积径流深度约为 12 mm·h^{-1}时,会产生等于或大于 90%以上的冲刷率.吸附在公路灰尘中的重金属颗粒物会随路面径流迁移到公路两侧土壤中,从而影响公路两侧土壤中重金属含量.研究发现,约 5%～20%来自机动车辆的污染物随径流排放进入地表水体或者渗入土壤 (Ball *et al*, 1998; Krein *et al*, 2000).

总体上讲,公路两侧土壤中重金属的含量及其分布格局是多种因素综合影响的结果.由于佛罗里达州坦帕高速公路受到当地局部气候、地形地貌、人工建筑物和绿化带等综合因素的影响,该公路两侧土壤中 Pb含量与日车流量并没有显著的相关性 (Hafen *et al*, 1996). Al-Chalabi等研究发现,尽管澳大利亚布里斯班 Ipswich公路车流量较 Southeast公路低,但其两侧土壤中 Pb含量比 Southeast公路的含量高;公路旁土壤中 Pb的含量与日车流量也没有正比关系 (图 3).这可能是因为 Ipswich公路的重型商业车辆所占总机动车辆的比例较高的缘故 (Al-Chalabi *et al*, 2000).

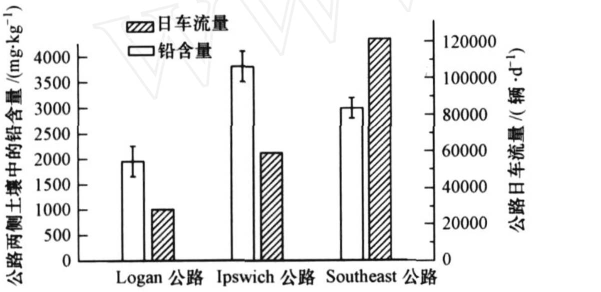


图 3　不同车流量对道路旁 Pb含量的影响 (根据 Al-Chalabi *et al*, 2000的数据重新做图)

Fig 3　Influence of different vehicle density on Pb concentration in roadside soils

4　公路两侧土壤重金属的分布特征 (Dispersion of heavy metals in roadside soils)

研究区域的气候、气象条件和地理位置不同,公路两侧土壤中重金属的分布会有差异.总体上讲,在公路两侧的土壤中,重金属的含量一般随着距公路距离的增加呈下降趋势.郭广慧等统计国内外的大量研究资料发现,公路两侧土壤中 Pb含量随距公路垂直距离的外延呈指数形式下降,重度污染与中度污染的临界点和中度污染与轻度污染的临界点 (距离)分别为距公路 10 m和 65 m (郭广慧等, 2007). Ideriah等研究表明,公路两侧土壤中重金属含量与距公路的距离呈负相关关系 ($r=0.958$, $n=17$) (Ideriah *et al*, 2004).

由于受公路两侧土壤的性质、公路周围植被等的影响,某些公路两侧土壤中的重金属在距公路几十米处已达当地背景值水平.根据不同的文献报道,公路两侧土壤中 Pb含量主要分布在距公路 0～50 m内,在距离公路 70～150 m以外基本达到当地土壤的背景值水平 (Leonzio *et al*, 1987; Warren *et al*, 1987; Swaileh *et al*, 2004; 李湘南等, 2000; 索有瑞等, 1996; 王金达等, 2003; 曹立新等, 1995) (图 4). Ozkan等发现,公路两侧土壤中 Pb含量集中分布在距公路 15 m的范围内,在距公路 30 m时公路土壤中 Pb含量趋于稳定,并接近背景值水平; Pb含量随着距公路距离的增加呈指数形式下降 (Ozkan *et al*, 2005). Münch研究发现,德国多特蒙德公路 (车流量为 3200辆·d^{-1})两侧森林土壤中 Pb、Zn和 Cd含量随距公路的距离呈指数形式下降,在距公路 10 m均已达到背景值水平 (Münch, 1993). Fakayode等研究发现,车流量大的公路两侧土壤中重金属含量高,且重金属含量随着距公路距离的增加呈指数形式下降; Pb、Cd和 Cu在距公路 50 m处基本达到背景值水平, Zn在 30 m处趋于背景值水平 (图 5) (Fakayode *et al*, 2003). Jaradat等研究发现,约旦安曼某公路两侧土壤中 Pb含量集中分布在距公路 1.5 m范围内, Pb、Cu、Zn和 Cd在距公路两侧 60 m处基本上趋于背景值水平 (Jaradat *et al*, 1999). Blok发现,公路两侧土壤中 Zn含量

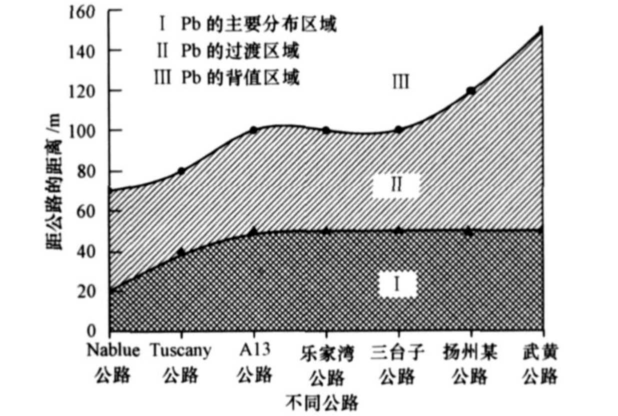


图 4　Pb在公路两侧土壤中的分布区域 (根据资料整理: Leonzio *et al*, 1987; Warren *et al*, 1987; Swaileh *et al*, 2004; 李湘南等, 2000; 索有瑞等, 1996;王金达等, 2003; 曹立新等, 1995)

Fig 4　Dispersion area of Pb in roadside soils

随距公路距离的增加呈指数形式递减,约 75%的 Zn 沉降在距公路 6 m的范围内,在距公路边 30 m处,土壤表层中 Zn的累积指数因子接近 1 (Blok, 2005).

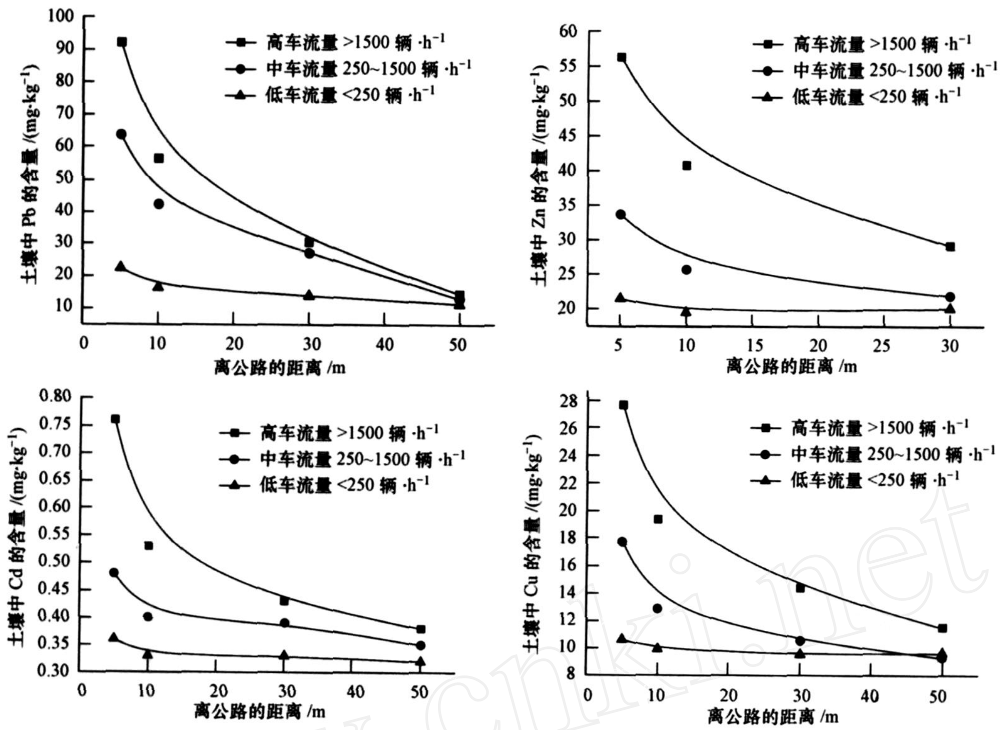
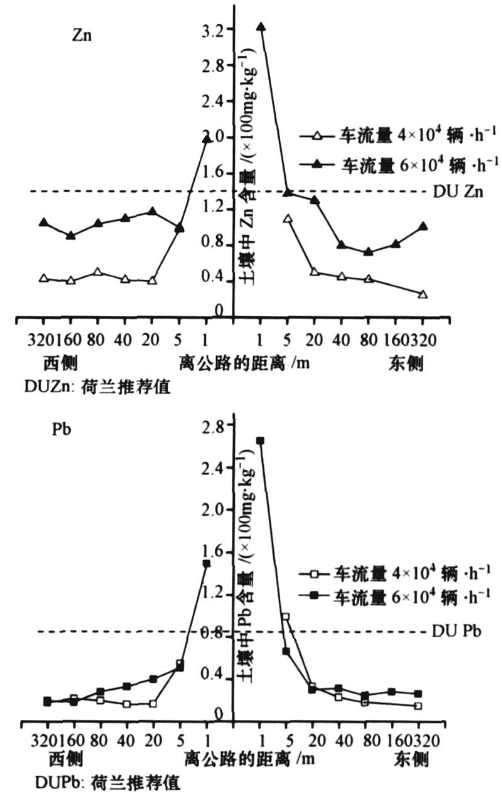


图 5 公路两侧土壤中重金属含量与距公路距离的关系 (根据 Fakayode *et al*, 2003的数据重新做图)

Fig 5 Relationship between heavy metals in roadside soils and distance from roadside

由于公路所处的地理位置和当地的气候气象的影响,公路交通排放的含重金属颗粒物可以扩散到公路周边更远的区域. Othman等研究表明,含铅颗粒物主要沉降在距公路 5 m内;如果在风的作用下,将飘移到更远的地方. 因此,他们建议,蔬菜应种植在离公路 200 m以外 (Othman *et al*, 1997). 林健等研究发现,公路旁土壤中 Pb含量在距公路 5~80 m范围内污染最严重,污染扩散范围约为 250 m左右 (林健等, 2000). Zechmeister等发现,在轻型车辆 (载重量 < 3 t)占总机动车辆 (车流量为 32227 辆 $\cdot d^{-1}$)的比例为 70.6%的某公路两侧, Mo、Cr和 Cu在距公路 1000 m处的苔藓中仍有积累 (Zechmeister *et al*, 2005). Viard等评价了某高速公路车流量为 4×10^4 辆 $\cdot d^{-1}$和车流量为 6×10^4 辆 $\cdot d^{-1}$两处的土壤重金属污染 (图 6) (Viard *et al*, 2004). 从图 6可以看出重金属集中分布在距公路 0~20 m,公路两侧土壤中重金属污染范围可以扩散到距公路 320 m处;受主导风向 (西风)的影响,公路东侧土壤中重金属的平均含量比西侧土壤高.



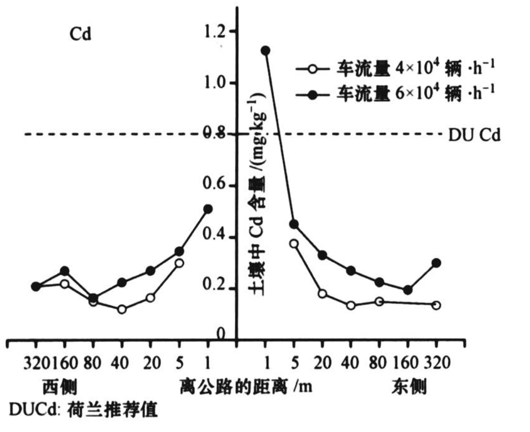


图 6　公路两侧土壤中 Zn、Pb和 Cd的分布 (根据 Viard *et al*, 2004的数据重新做图)

Fig 6　Dispersion of heavy metals such as Zn, Pb and Cd in roadside soils

6　结论 (Conclusion)

公路交通排放的重金属主要来源于含铅汽油和润滑油燃烧、汽车轮胎和刹车里衬机械磨损. 公路两侧土壤和灰尘中 Pb、Cu、Zn和 Cd的含量和分布,除与当地土壤母质有关外,主要受交通流量、车辆类型、地形与路面状况、绿化带配置等交通状况和风、降雨等气象条件的影响. 大致而言,公路两侧土壤中重金属含量随着距公路距离的增加呈指数形式下降.

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