

煤矸石自燃的关键影响因素及治理方法研究现状

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摘 要:煤矸石作为煤炭的伴生产物,长期堆存过程中自燃现象频发,直接或间接产生生态污染、水体污染、地质灾害等诸多问题,造成巨大经济损失和人员伤亡。煤矸石从堆积初期到燃烧状态受诸多因素影响,包括自身性质、自燃条件和外部环境等,是一个复杂的物理化学反应过程。为提高煤矿矿区矸石自燃的防治能力,分析了煤矸石自燃理论的研究现状,系统总结了现阶段国内外学者对煤矸石自燃机理和治理方法的研究进展。围绕可燃物、氧气、温度3个影响煤矸石自燃的必要因素,提出了引发自燃的主要关键影响因素和作用过程机理。较全面介绍已有煤矸石山自燃防治的主要方法,对比分析了各种常规煤矸石自燃灭火手段以及治理技术的优缺点,指出了常规简单技术治理效果的局限性。针对煤矸石作为砂、石等替代材料,回填露天矿坑、采煤塌陷区等区域进行土地整治和生态修复,提出在防治过程中要明确自燃治理的控制对象,提升防灭火材料的特定性能,通过智能化设备提高辨识准确性进行精细化监控,并运用多种监测预警技术协同自燃防治材料多手段多方法运用综合治理,并提出了煤矸石自燃防治技术的未来发展和矿用防灭火材料的研究方向,为后续开展煤矸石自燃机理研究及自燃防治工程应用提供参考和理论支持。

关键词:煤矸石;自燃过程;控制对象;治理方法

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Research progress on the key influencing factors of spontaneous combustion of coal gangue and control methods

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Abstract: Spontaneous combustion phenomenon of coal gangue as an associated product of coal is frequent in the process of long-term stockpiling, which directly or indirectly produces ecological pollution, water pollution, geological disasters and many other problems, resulting in huge economic losses and human casualties. Coal gangue is a complex physical and chemical reaction process that is influenced by many factors, including its own properties, self ignition conditions, and external environment, from the initial stage of accumulation to the combustion state. In order to improve the prevention and control of spontaneous combustion of gangue in mining areas, the research status of the spontaneous combustion theory of coal gangue was analyzed. The research progress of scholars at home and abroad on the mechanism of spontaneous combustion of coal gangue and governance methods at this stage was systematically summarized. The main key influencing factors and process mechanisms that trigger spontaneous combustion were presented focusing on three necessary factors affecting the spontaneous combustion of gangue, combustibles, oxygen, and temperature. A more comprehensive introduction was given to the main methods of prevention and control of spontaneous combustion in existing gangue mountains. The advantages and disadvantages of self ignition fire extinguishing methods of various conventional coal gangue and treatment technologies were compared and analyzed. The limitations of the effectiveness of conventional techniques for treatment were pointed out. The land remediation and ecological restoration are disposed of in response to coal gangue replacing sand and stone materials for backfilling areas such as open pits and coal mining

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subsidence areas. It is proposed to identify the control targets for spontaneous combustion management in the prevention and treatment process, enhancement of specific properties of fire protection materials, intelligent equipment to improve the accuracy of identification of fine monitoring, and the use of a variety of monitoring and early warning technology synergistic spontaneous combustion prevention and control materials. The future development of coal gangue spontaneous combustion prevention and control technology, the research direction of mining fireproofing materials were proposed, providing reference and theoretical support for the subsequent research on the mechanism of spontaneous combustion of coal gangue and the application of spontaneous combustion control engineering.

Key words: coal gangue; spontaneous combustion process; control targets; control methods

0 引言

中国是煤炭生产和消费大国,据中国煤炭工业协会发布的《2022 煤炭行业发展年度报告》,2022 年煤炭产量高达 45.6 亿 t,创历史新高,煤矸石资源综合利用率为 73.2%。煤矸石是煤矿在开拓掘进、采煤和煤炭分选等生产过程中排出的含碳岩石,是煤矿生产过程中的废弃物,其产生量占煤炭生产总量的 10%~15%^[1],累计存量已超 70 亿 t^[2],现已明令禁止建设永久性煤矸石堆放场。《关于“十四五”大宗固体废弃物综合利用的指导意见》明确指出,提高大宗固废资源利用效率,创新大宗固废综合利用模式。在煤炭行业推广“煤矸石井下充填+地面回填”,促进矸石减量。临时堆放或未能资源化综合利用的煤矸石,会造成资源浪费,并引发一系列生态环境问题。自燃会产生飞灰、酸化等问题,释放大量的有毒有害气体、PM_{2.5} 颗粒物、重金属离子等,污染周围空气、土壤和水体,是潜在的生态环境安全隐患^[3-6]。更严重的是,矸石山自燃后内部堆积结构发生改变,会引发山体崩塌、滑坡、泥石流等次生地质灾害,危害人类的居住环境和生命健康^[7-10]。

近年来,大量煤矸石自燃机理研究表明,影响煤矸石自燃的主要因素为可燃物、助燃物及温度^[11-12]。需从源头认识自燃发生的机理,提升煤矸石自燃的治理技术。虽然众多学者研究了煤矸石自燃机理和治理方法,但存在较多争议。自燃的传统治理方法过于简单,现行治理手段的长效监测和治理机制水平有待提升,仍需结合自燃必要条件进行深入的系统研究。

笔者结合煤矸石自燃的主要关键影响因素和作用过程,综述了自燃的主要成因和现代治理方法,剖析了单一治理方式的局限性,指出了综合治理方法的精准、高效等优点,为后续的机理研究及自燃治理工程应用,提供理论支撑和指导作用。

1 煤矸石自燃机理

煤矸石自燃机理目前主要有黄铁矿理论、细菌

作用理论、自由基理论、挥发分理论和煤氧复合理论等 5 种主流学说。

黄铁矿理论通过研究其氧化时发生的电极反应,揭示了形成亚铁离子和硫酸盐离子的过程机理^[13]。细菌作用理论认为,细菌可大幅加速煤矸石中含硫矿物的氧化,促进自燃进程^[14]。自由基理论表明自由基与氧气反应破坏了其中的化学键和官能团,导致旧自由基消灭并被强活性新自由基取代,自由基逐渐累积引发连锁反应,其浓度急剧上升后反应加速、能量积聚导致自燃^[15]。只有关键的活性自由基被消除后环链反应才会终止^[16]。挥发分理论揭示了煤矸石在燃烧过程中随温度改变,向大气排放芳香族、脂肪族以及含氧官能团等挥发性有机物质,使环境发生改变促进自燃^[17]。煤氧复合机理论述了煤矸石周围充斥不均匀分布的氧气、水蒸气等,在低温下氧气被输送到煤矸石颗粒表面和孔隙中,并发生煤氧相互作用,发生氧化自热,并自动加速,当氧化产生的热量积聚,无法及时散发则导致煤矸石自燃^[18]。

自燃演化机制是煤矸石所含的可燃物发生氧化反应并逐渐累积能量,最终达到燃点发生燃烧的过程。煤矸石由自热逐渐演化为自燃,完成从量变到质变的积累转化。煤矸石的氧化自燃过程受多种因素影响,是复杂的作用过程和多因素耦合的结果^[19],如图 1 所示。自燃分为 2 个阶段。在初期的潜伏阶段,氧气在煤矸石内部的缝隙和孔道进行物理吸附和化学吸收,与所含可燃物质发生缓慢氧化并放热。在此过程中,少量氧化热被外部环境消散,但当数以百万吨计的煤矸石发生氧化,内部热量无法及时释放便会发生积聚^[20],达到临界温度后反应过程加速。在自燃阶段,煤矸石达到燃点便开始燃烧,自燃不断扩大发展,挥发分产率随热解温度的升高而增加,挥发分、固定碳开始燃烧,旧自由基不断向新自由基转化,引起更广范围的燃烧。

煤矸石自燃的演化过程中,与其自身理化特性和外界环境有关^[21]。当煤矸石中的有机物质发生氧化反应,所释放能量大于向外界散失的能量,温度

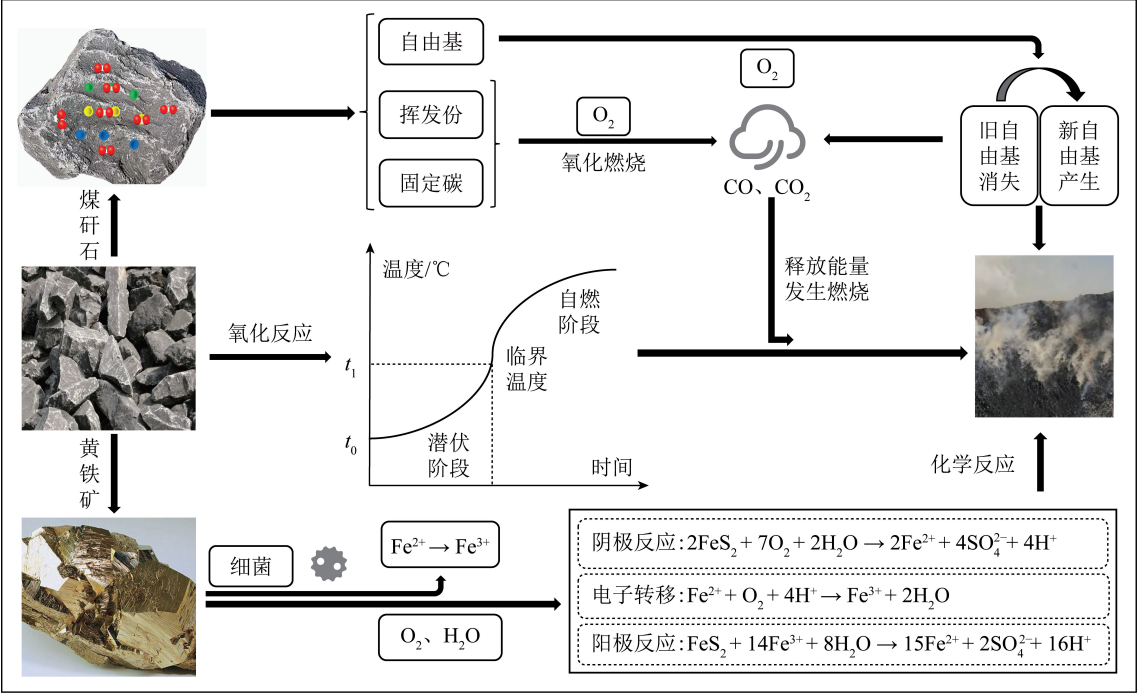


图 1 煤矸石自燃因素主要作用过程和机理

Fig.1 Main process and mechanism of spontaneous combustion of coal gangue

逐渐升高^[22]。氧气含量不同也使燃烧特点发生改变^[23]。温度升高后煤矸石中挥发性物质和多环芳烃释放行为也不相同^[24]。煤矸石还具有高灰分、低热值、低挥发分等特点且难以实现稳定着火和完全燃尽^[25-26]。研究与揭示煤矸石自燃的形成过程与演化机理,是采煤矿区煤矸石自燃预防和治理的理论基础。因此需全方面研究影响自燃的因素。

2 煤矸石自燃的关键影响因素

煤矸石主要是由 SiO₂、Al₂O₃ 构成,其次含少量

Fe₂O₃、CaO 等其他物质,见表 1。由于地域差异和形成地质年代不同,煤矸石在成分上也有所差异^[25]。煤矸石自燃离不开以下必要条件^[36]:① 煤矸石中含有能够满足燃烧的可燃物质;② 煤矸石堆中的通风间隙和孔道能为燃烧提供所需氧气;③ 煤矸石在氧化过程中产生的热量不能及时散失到外界环境中,温度不断升高最终达燃点。图 2 展示了煤矸石氧化基本发展过程。从煤矸石自燃关键影响因素出发,阐述自燃的发展过程和变化机理。

表 1 煤矸石的主要无机化学成分

Table 1 Chemical composition of coal gangue

国家	省份	w(SiO ₂)/%	w(Al ₂ O ₃)/%	w(Fe ₂ O ₃)/%	w(CaO)/%	w(MgO)/%	w(TiO ₂)/%	w(SO ₃)/%	文献
中国	内蒙古自治区	31.77	42.55	0.27	1.23	0.09	0.51	—	[27]
	山西	71.60	15.01	3.72	3.81	1.64	—	—	[28]
	北京	49.41	21.32	6.02	2.52	1.56	0.94	0.65	[29]
	陕西	49.50	33.33	7.60	6.09	0.97	0.83	—	[30]
澳大利亚		59.24	23.41	9.53	2.16	1.16	—	0.45	[31]
波兰		58.95	20.50	6.63	0.35	1.93	1.05	0.17	[32]
巴西		55.91	24.81	8.73	0.28	—	—	2.11	[33]
印度		52.70	22.60	6.37	2.45	1.22	—	0.43	[34]

2.1 煤矸石中可燃物质及矿物质的影响

煤矸石组成成分的性质是影响其自燃的重要因素之一。煤矸石中所含固定碳、挥发分等物质为自燃提供了先决条件^[37]。硫铁矿和其他矿物质也会改变燃烧过程^[38]。矿物的成分和内部微观样貌随

温度的升高而发生改变,从而影响燃烧状态。此外,煤矸石作为煤的伴生产物,自燃倾向性也受煤质影响。随变质程度增大,煤中芳香环含量增加,含氧官能团和杂质减少,煤的反应性和自燃倾向性降低^[39]。

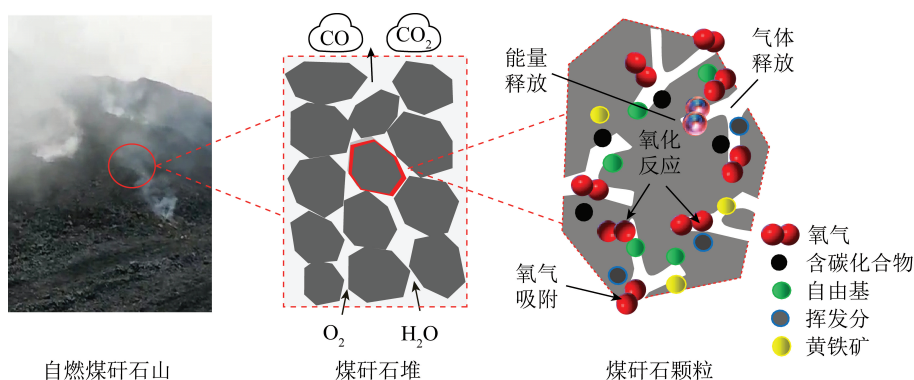


图2 煤矸石氧化的基本过程

Fig.2 Basic process of coal gangue oxidation

2.1.1 可燃物质的影响

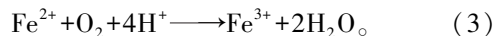
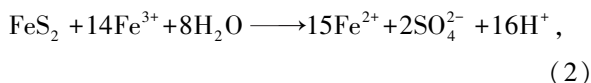
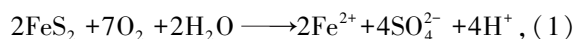
煤矸石中的有机质,如挥发分、固定碳等为自燃提供必要的可燃物质。ZHANG等^[40]发现煤矸石中含有较多的有机质,如含氧官能团、挥发分和硫化物等。GAO等^[41]将煤矸石处理成不同粒径球形颗粒样品进行着火试验,发现单体煤矸石会释放有机质、挥发性物质,且能够被点燃。FABIAŃSKA等^[42]在检测长期自热和风化的煤矸石山释放的气体中,发现大量有机化合物的挥发分,研究表明这些化合物并非直接来自有机物,而是在有机物热解过程中合成。挥发分产率随热解温度升高而增加^[43],使燃点附近温度快速上升并引起更广范围的燃烧。

GONG等^[44]研究认为煤矸石在400~630℃发生挥发分和固定碳的燃烧引起质量损失。挥发分和固定碳的燃烧有先后顺序,SONG等^[45]和ZHANG等^[46]研究发现挥发分燃烧一般早于固定碳,挥发性物质在400~480℃燃烧,而固定碳在480~650℃燃烧。低温氧化阶段,烷基侧链、桥键、含氧官能团等氧化裂解生成CO和CO₂等气体。而高温氧化阶段,有机质发生裂解生成烷烃类气体,并优化自燃的燃烧条件,产生协同效应并提高燃烧的综合效率^[47]。煤矸石自燃后,总质量损失与挥发性物质和固定碳含量一致。此外,具有较高挥发率、良好燃尽性能的煤矸石更易着火。

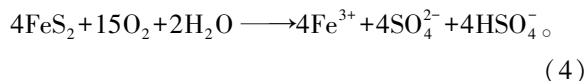
2.1.2 矿物质的影响

黄铁矿是煤矸石中硫的主要存在形式,通过直接氧化或氧化亚铁硫杆菌催化氧化的方式发生反应^[48]。煤矸石中的硫在含有氧气和水的环境中,低温条件下生成不稳定的硫煤化合物,使FeS₂通过催化氧化反应促使电子发生转移^[49],Fe²⁺加速向Fe³⁺转化并生成SO₂及SO₄²⁻,并释放能量^[50]。反应过程中生成的低挥发性酸性物质为菌株提供了适宜的生长环境,滋生氧化亚铁硫杆菌^[51]。微生物菌起催化

作用,导致反应进入连续自氧化的高速循环阶段^[52]。FeS₂可提高氧化速率,PIETRZAK等^[53]研究表明不同含量FeS₂对自燃的影响也有区别,质量分数为2%时,促进自燃效果作用最明显。涉及的反应^[54]主要有



总反应式为:



煤矸石所含其他无机矿物质也会影响自燃过程。随燃烧温度升高,矿物质在一定温度下发生分解^[55]。ZHANG等^[56]利用热分析法研究了11种煤矸石的燃烧行为和过程,发现失重阶段可燃物被氧化并发生燃烧,同时矿物质进行脱羟基反应,颗粒中高岭石、伊利石和方解石热分解时发生吸热反应从而抑制燃烧过程。XU等^[57]发现相较伊利石型煤矸石,高岭石型煤矸石的热解所需起始温度低,挥发分释放更强烈,热解性能更好。清晰、深入地研究物质成分和含量,有利于进行煤矸石处理和自燃治理。

2.2 氧气的影响

氧气含量影响煤矸石自燃程度。TANG等^[58]研究指出煤矸石在贫氧条件下,氧化过程被抑制,但氧化反应仍持续并释放热量。自燃初期阶段的氧化反应和能量积累是一个缓慢的过程。煤氧复合理论认为煤矸石与氧气结合过程十分复杂,属于在贫氧、中低温的条件下缓慢的氧化过程^[59]。矸石山体内部由于较低的氧气浓度限制,低氧浓度下的煤矸石处于阴燃状态,JIANG等^[60]发现燃烧位置位于山体表层以下的非燃烧区和预热区之间。在富氧条件下的O₂/CO₂气氛中,温度升高会降低煤矸石的点火延

迟时间和内部点火温度;但随 O_2 浓度增加,挥发分的燃尽时间缩短^[61]。挥发性火焰高大明亮,燃烧速率增加,燃点和燃尽点向较低温度转移,短时间内可实现完全燃烧^[62]。氧气的物理吸附、化学吸附促使自燃发生,反应过程中始终伴随能量演化。

煤矸石堆积形成不同的孔隙会改变供氧条件,也影响矸石山自燃倾向。矸石山内部矸石堆积松散、无序,外界风凭借间隙、裂缝为山体内部提供充足的氧气,加强了与外界连通的传质、传热和流体流动行为^[63]。氧气在煤矸石内部的缝隙和孔道进行物理吸附和化学吸收,发生煤氧复合反应并放热。煤矸石颗粒越小表面积越大,其自身多孔结构增加了氧气与可燃物质的接触面积和反应位点,为氧化反应提供更多空间^[64]。由此可见,氧气浓度、供氧速度影响煤矸石氧化状态并控制后续燃烧过程。

2.3 温度的影响

温度是改变燃烧进程的关键因素。LI 等^[65]研究发现煤矸石的某些热物理性质在 70 ℃ 发生改变,超过这个临界温度后,氧化反应加剧、升温速度加快、能量迅速积聚^[66-67]。温度升高过程中,煤矸石物理脱附减弱、化学吸附增加,特定温度下产生气体浓度发生变化。

温度升高后促进热解行为。自燃过程中多种多环芳烃释放量先升高后降低^[68]。热源作用下的煤矸石孔隙率随温度升高而增大,有机大分子和其他小分子受热时开始分解或分裂产生新的中间过渡产物,促进整个自燃过程向更深的方向蔓延^[69]。LI 等^[70]选取自燃点附近和新鲜状态的 2 种矸石样品,通过 TGA 和 DTG 发现在 310~760 ℃ 时快速燃烧,氧化反应速率增加并进入有机物分解阶段。温度不仅是煤矸石自燃过程中关键特征参数,还是氧化反应进行的尺度标准,影响煤矸石的失重率、气体产生率和官能团变化规律等。

3 煤矸石自燃治理方法现状

煤矸石的自燃治理过程实质上是控制其自燃主要因素的过程,可通过消除氧气或降温等措施来降低自燃风险,消除自燃引发的危害。移除火源、水力灭火等简单灭火方法具有易复燃性、局限性、不能根治等特点。如今煤矸石自燃治理已从单一手段治理发展为多手段、全方位的综合治理模式^[71]。监测检测技术也从初级的打孔探测发展为使用热红外成像法、标志气体法等更为先进的监测检测技术,已形成多手段监测预警技术与自燃治理方法相结合的综合治理模式^[72],灭火效率显著提高,经济损失显著降

低,为煤矸石自燃治理的工程应用提供了新途径。

3.1 已有自燃煤矸石山治理方法

3.1.1 单一治理方法

早期自燃的煤矸石处理以灭火为主,几乎不考虑自燃的预防和长效治理。以去除火源、降温、隔氧为目的的矸石自燃治理,采用挖除火源、水力灭火、黄土覆盖、打孔注浆和注入惰性气等简单的治理方式^[73-74]。矸石山治理后复燃率较高。

一般来说,挖除火源法是最直接、最有效的降温方法。一旦确定自燃区域后,将自燃的煤矸石挖出冷却,经处理后回填。这种方法的局限性大且操作困难,只适用于自燃初期阶段,自燃面积大和温度高的区域不适合使用这种方法^[75]。

多数煤矿也会使用水力灭火法处理煤矸石山自燃,但这种方法无法控制水流流向,自热和燃烧部位无法得到有效降温和灭火,注水时还易发生水煤气爆炸,自燃后山体内部的空隙变大使供氧充分,灭火后更易复燃。

煤矸石山表面覆盖黏土或黄土,通过压实隔绝空气进入,山体内部空气耗尽后,燃烧的煤矸石就会因缺氧而熄灭^[76]。一旦覆土出现裂缝后无法起到密封作用。覆土法的特点是成本低、操作简单^[77]。

打孔注浆灭火法也是常用方法之一。利用浆体的流动特性充填矸石山空隙并形成包裹层隔绝氧气,使煤矸石不具备燃烧条件,实现阻燃和灭火的效果^[78]。

此外,还可注入泡沫灭火剂^[79],隔绝氧气、降低温度达到快速灭火目的。注入惰性气体法是将惰性气体注入自燃区域,液氮气化或干冰升华后体积急剧膨胀,高温气体被快速降温、置换,使着火区域隔绝空气而窒息^[80]。此方法降温持久、效果明显且作用范围大,但原料成本高、需求量大和供应易受限。

整体来说以上方法比较单一,控制操作过程比较简单,但局限性较强、复燃可能性大、效果不佳,不能形成长效防治机制。

3.1.2 综合治理方法

煤矸石自燃的简单治理方法基于现代技术的发展,对已有煤矸石的治理监测,充分利用热红外、无人机等科学监测技术,协同抑制剂、杀菌剂、凝胶材料等,结合覆土、分层压实、注浆等隔氧阻燃手段形成了综合治理的方法。

对已有矸石山自燃以监测温度为主,以检测逸出气体种类、标识气体等方法为辅。温度传感器、红外热成像、卫星遥感等方法都能准确、高效地获得煤矸石堆表面温度及变化情况。

红外热成像技术通过图像能够呈现煤矿排矸场

表面温度的分布情况^[81],结合近景摄影测量技术能够构建地表温度分布的三维可视化模型,监测和定位煤矸石热异常所潜在的风险区域,非接触性、定位精确和经济适用性强是该方法的显著特征^[82]。大面积的排矸场,可通过连续气体热监测和定期热成像研究,进行火灾风险控制,利用浸入式温度计和气体浓度传感器收集矸石山内部数据,进行自热自燃的发展趋势预测^[83]。随 3D 可视化技术、5G 技术协同卫星遥感、无人机监测技术的快速发展,已创造性地应用于煤矸石堆地表及裂缝处温度数据的监测、收集和传输^[84]。WANG 等^[85]采用氢浓度参数结合井

温检测技术确定高温区,将氢浓度和温度测量值作为主要参数,并运用克里格数据插值法处理,得到温度和氢浓度的空间分布图,运用综合手段分析煤矸石山的火情区域、趋势走向和燃烧的风险程度。图 3 为白吉沟矿区煤矸石山热红外图像,红色为高温区域^[86]。此外无人机协同氢浓度等技术的使用已成为监测手段之一,获取自热自燃区域的相关数据,并利用监测分析技术,进行风险评估分析。对现场气体毒性、爆炸风险和火灾趋势进行准确预警、监测和评价,建立了矸石自燃危险性的毒性-危险性-火灾趋势评价体系。

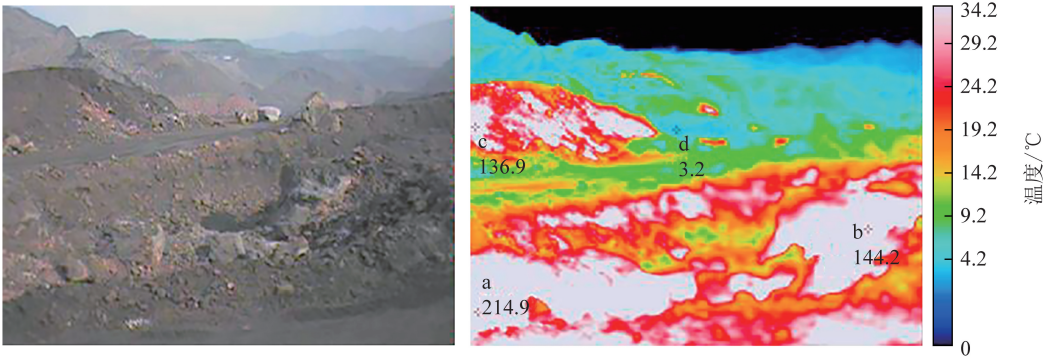


图 3 白吉沟矿区煤矸石自燃热红外图像^[86]

Fig.3 Infrared imaging of gangue spontaneous combustion area in Baijigou coal mine^[86]

3.2 新建煤矸石回填场自燃防治研究进展

煤矸石可替代砂、土等作为主体材料,回填露天矿坑、采煤塌陷区、天然坑洼区等区域,再表面覆土进行生态修复。在回填过程中采用矸土混排、分层碾压覆土方法,或注入低强度浆体材料,形成煤矸石自燃预防和长效治理体系。

利用煤矸石、粉煤灰等固体废弃物对矿区塌陷进行修复,将待处理区域进行剥离表土,充填后再表土回填并机械压实。煤矸石进行处理后分层堆放,层与层之间和表面用黄土隔离并压实,通过外加剂调控回填材料性能,将配有外加剂的材料对治理区域注浆,如图 4 所示。



图 4 打孔注浆施工

Fig.4 Perforated grouting construction drawings

在整治过程中使用夯实围山、台阶式整地、回填复垦等方式,覆盖黄土或泥土并注入浆体以减少通风来防止自燃^[87],如图 5 所示。这种方法提升了灭火实际效果,降低了工艺操作成本,还有效防止燃烧区域再次复燃,便于生态复垦的实施和应用。

气体阻隔性能好等特点被广泛研究和应用。HUANG 等^[88]采用溶液插层聚合法制备的聚丙烯酰胺-蒙脱土聚合物纳米复合缓蚀剂,有效抑制煤矸石表面活性基团的氧化活性,提高煤矸石的热稳定性,克服抑制剂寿命短的缺点。表面抑制剂、表面缓蚀剂等喷洒在煤矸石外部抑制氧化自燃^[89]。高吸水

高分子纳米复合材料因其密度低、热稳定性高、



图 5 黄土覆盖、台阶式整地

Fig.5 Loess cover and stepped land preparation

性的膨润土-丙烯酰胺水凝胶可有效削弱煤矸石中各种含氧官能团(如 Si—O 和 O—H)的活性,高含水量可带走反应热,具有冷却和燃烧控制效果^[90]。复合粉煤灰凝胶以水、粉煤灰、复合凝胶添加剂和悬浮剂为原料,结合注浆、封堵等方法抑制煤矸石放热和燃烧,进行自燃预防和治理。同时可将凝胶灭火和泡沫灭火技术相结合^[91],将泡沫作为凝胶载体,这样从隔氧降温的灭火角度,既降低了成本又充分发挥 2 种灭火技术的优点。

微生物媒介作用下的黄铁矿氧化,是导致酸化和自燃的关键过程。硫杆菌类细菌在碱性环境里生长困难,抑制煤矸石自燃,可使用杀菌剂杀死氧化亚

铁硫杆菌并抑制氧化反应^[92]。将含有碱性物质的注浆材料,通过打孔注浆技术将浆体注入自燃煤矸石山内部,渗透和扩散后与燃烧释放的 SO₂、CO₂ 等酸性气体反应生成硫酸钙、碳酸钙等^[93]。不但可填充矸石山内部空隙,还可附着在煤矸石周围形成牢固的包裹层,密封隔绝外界氧气达到防止煤矸石自燃的目的。

凭借现代技术手段,运用灭活、抑菌绿色环保外加剂材料,辅以物理、化学方法,通过隔氧、降温等手段源头治理、协同处置。逐步建立已有煤矸石山、煤矸石回填及煤矸石生态复垦区域自燃风险的长效治理体系(图 6)。

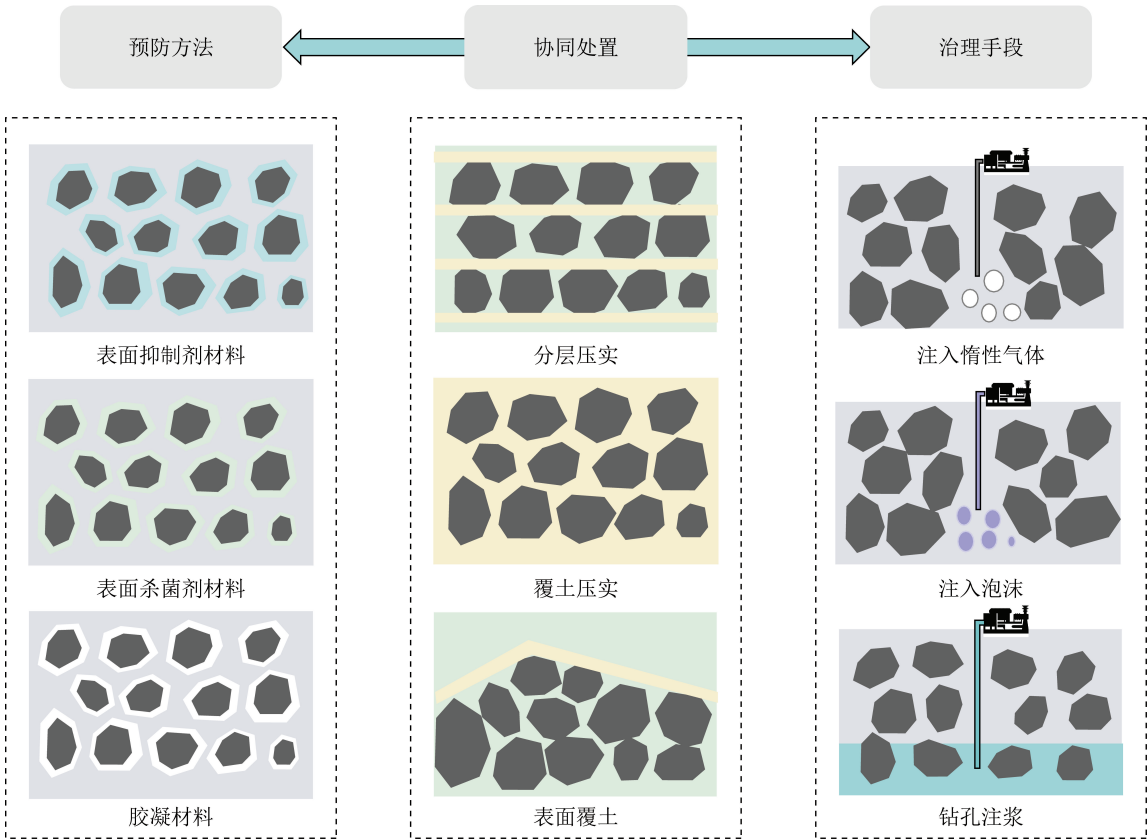


图 6 煤矸石自燃治理技术

Fig.6 Coal gangue spontaneous combustion control technology

4 结 论

目前,国内外学者从煤矸石自燃机理、综合治理和自燃防治等方面进行了深入研究,取得了丰富成果。随着国家“双碳”政策和环保政策的出台,政府整治生态环境的决心更加坚定,大宗固体废弃物的处理处置问题越来越受到重视。因此,防治、监测技术精准化和材料绿色化成为煤矸石自燃防治及回填应用的必然要求。依据煤矸石自燃的关键成因和治理技术进行了归纳总结,得出以下结论:

1)煤矸石的自燃因素存在相互关联,可燃物、氧气和温度等关键因素决定了自燃过程和发生机理。通过提升设备识别精度,降低矸石中残存煤量减少可燃物,也可控制氧气含量遏制自燃进程,采用改性注浆材料降低矸石山空隙,控制含氧量及抑制升温,从根本上解决自燃。

2)在监测防治方面,借助可视化监测装备并与多种灭火技术相结合,精细化监控温度、指标气体等变化情况,分级预警准确辨识火源。防治方法由单一向多种方法综合治理转变。

3)在绿色材料防治方面,积极改进治理技术,从剔除可燃质、隔氧和控温角度,研发低成本、环境友好型矿用防灭火注浆材料或回填材料。建立健全防治体系和治理效果评价机制,进一步提升自燃预防和生态治理的目标。

4)资源化利用是处置煤矸石的最佳方式。无害化处置的煤矸石用于采煤沉陷区、塌陷坑等土地整治、地面回填或生态修复,既能解决煤炭开采带来的地质问题,又能实现煤矸石大规模消纳及高值化利用。

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