**煤炭转化**

# 低阶烟煤对常规炼焦煤热塑性影响规律研究

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**摘　要**:为提高低灰低硫低阶煤的配煤炼焦用量,在低阶烟煤煤岩分离的基础上,研究了低阶烟煤镜质组对气煤、肥煤、焦煤等常规炼焦煤塑性胶质体的流动性、膨胀性和黏结能力等影响。结果表明,随着低阶烟煤镜质组比例的增加,气煤、肥煤、焦煤塑性胶质体的流动性、膨胀性和黏结力指数下降。低阶煤镜质组的比例为12%时,所得气煤配低阶煤镜质组的流动性下降70.0%,黏结指数下降31.8%;所得肥煤配低阶煤镜质组的流动性下降66.1%,黏结指数下降9.4%;所得焦煤配低阶煤镜质组的流动性下降78.4%,黏结指数下降45.7%。配入低阶煤镜质组比例为8%时,气煤的膨胀度由1.3%降至-19.5%,肥煤的膨胀度由158.7%降至88.2%,焦煤的膨胀度由28.5%降至-1.2%,呈现劣化作用。所得配煤指标并不存在线性关系,对焦煤影响最大,交互作用偏负;对肥煤影响较小,交互作用偏正。

**关键词**:低阶烟煤;炼焦煤;热塑性;黏结性
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# Influence rule of low-level bituminous on thermoplasticity of conventional coking coal

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**Abstract**: In order to improve the addition of low-ash low-sulfur para-bituminous coal during coal blending, the influence of para-bituminous coal vitrinite on mobility, expansion and caking index and other factors of conventional coking coal which were gas coal, fat coal, coking coal were investigated. With the increase of vitrinite, the above three indexes decreased. When the vitrinite was 12%, the mobility of gas coal, fat coal, coking coal decreased by 70.0%, 66.1%, 78.4%, and the caking index decreased by 31.8%, 9.4% and 45.7%. When the addition of vitrinite was 8%, the expansion of gas coal, fat coal, coking coal reduced from 1.3% to -19.5%, from 158.7% to 88.2%, from 28.5% to -1.2%. There was no linear relationship among the indexes. The change of vitrinite amount had the largest impact on coking coal, the interaction was negative. The change of vitrinite amount had the smallest impact on fat coal, the interaction was positive.

**Key words**: para-bituminous coal; coking coal; thermoplasticity; caking property

## 0　引　言

受优质炼焦煤资源和价格的影响,低阶烟煤已用于配煤炼焦,其冶金焦炭的性质指标在数值上虽与炼焦煤接近,但微观结构如光学组织差异明显,表明低阶烟煤对常规炼焦煤熔融黏结行为的影响规律仍需探究。长期以来对低阶烟煤的研究主要侧重于液化和低温热解方面[1-3],煤岩学及其活性组分的

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研究也针对常规炼焦煤而言[4-5],因此研究低阶烟煤对常规炼焦煤热塑性的影响规律对指导配煤炼焦具有重要的意义[6]。基于煤岩学观点,煤由多种煤岩显微组分组成[7-9],且不同煤岩组分的热解行为差异较大[10]。煤岩组分中镜质组和惰质组所占比例较大,镜质组也常作为活性组分看待,其在热解过程中能充分软化熔融形成胶质体组分,惰质组则在热解过程中多形成丝炭和破片组织。前苏联学者阿莫索夫将煤中镜质组、稳定组与 1/3 半镜质组划分为活性组分,丝质组、半丝质组与矿物划分为惰性组分,为大多数研究者所接受和采用。上述观点近年来受到质疑,有学者研究发现国内西南地区炼焦煤中半镜质组没有活性,低阶烟煤的镜质组活性有限。炼焦煤中稳定组分含量一般不超过 5%,对成焦过程的作用有限,镜质组含量一般超过 50%,因此是研究炼焦煤黏结性的重要对象。姚伯元等[11]研究了不同变质程度煤镜质组的活性。袁帅等[12]研究了不同变质程度煤热解最初阶段热解气的产率。深田等[13]研究表明快速加热能够改善弱黏煤的黏结特性。有学者提出烟煤容纳惰性物质的能力间接反映了烟煤的胶质体质量[14-15],通过测定 11 种不同变质程度烟煤在改变惰性物质含量下的黏结指数,确认了黏结指数与惰性物质含量呈曲线变化的规律。低阶烟煤如长焰煤、不黏煤等基本不具备黏结特性,参与配煤炼焦时一定程度降低了炼焦煤黏结性,故笔者以低阶烟煤和气煤、肥煤、焦煤为原料,研究低阶煤显微组分对 3 种炼焦煤热塑性的影响,探究低阶煤中活性组分对黏结行为的影响规律,为合理利用低阶煤提供理论依据。

## 1 试 验

### 1.1 试验煤样及设备

低阶烟煤取自神华集团不黏煤,常规炼焦煤包括蒋庄气煤、山西肥煤、安徽焦煤 3 种,煤样基本性质见表 1。

表 1 试验煤样基本性质

Table 1 The basic properties of experimental coal

| 煤样 | $M_{ad}$/% | $V_{daf}$/% | $A_d$/% | 黏结指数 $G$ |
|---|---|---|---|---|
| 不黏煤 | 11.03 | 29.97 | 7.25 | 0 |
| 气煤 | 2.97 | 37.12 | 9.10 | 70 |
| 肥煤 | 1.89 | 37.17 | 10.04 | 86 |
| 焦煤 | 1.23 | 24.70 | 11.30 | 78 |

试验设备主要有高速离心机、马弗炉、傅里叶红外分析仪等。

### 1.2 试验方法

低阶烟煤煤岩显微组分分离采用密度法,煤样粉碎到 1.0 mm 以下,采用密度 1.30 g/cm$^3$ 氯化锌溶液高速离心分离,所得上浮物再用 1.20 g/cm$^3$ 氯化锌溶液分离下沉得到镜质组。煤中显微组分定量分析在自制的 HY003 型光度计上参照 GB/T 15588—2013《烟煤显微组分分类》方法进行测定。

采用奥阿膨胀度、基氏流动度和黏结指数等分析单种煤及配煤的热塑性。自定义黏结力指数($GI$)是将国标黏结指数的试样质量增至 24 g,以提高小比例配煤成分的均匀性和稳定性。试验方法和步骤与 ISO 15585—2006《无烟煤黏结指数测定》类似,碳化坩埚为 50 mL 陶瓷坩埚,I 型转鼓设计为转鼓长 300 mm,内径 70 mm,转速 25 r/min。采用红外分析仪对低阶煤及其显微组分进行 FT-IR 傅里叶红外分析。

## 2 结果与讨论

### 2.1 低阶烟煤特性

低阶烟煤及显微组分的基本性质见表 2。

表 2 低阶煤基本性质

Table 2 The basic properties of low rank coal

| 样品 | 工业分析/% | | | 黏结指数 $G$ | 显微组分含量/% | | |
|---|---|---|---|---|---|---|---|
| | $M_{ad}$ | $V_{daf}$ | $A_d$ | | 镜质组 V | 壳质组 E | 惰质组 I |
| 原煤样 | 11.03 | 29.97 | 7.25 | 0 | 58.2 | 62.8 | 37.2 |
| 镜质组 | 3.49 | 35.37 | 3.48 | 43 | 76.0 | 76.7 | 23.3 |
| 丝质组 | 4.78 | 26.42 | 7.76 | 0 | 23.6 | 23.6 | 76.4 |

由表 2 可知,低阶烟煤灰分较低,没有黏结性;其镜质组显示出黏结特性,$G$ 值达到 43,镜质组挥发分增加明显,灰分降低;而丝质组灰分较高,挥发分偏低,无黏结特征。

低阶煤镜质组、丝质组和原煤的红外光谱分析如图 1 所示。

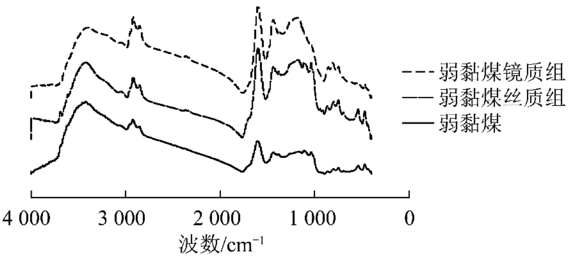


图 1　低阶煤及其显微组分红外光谱

Fig. 1　Infrared spectrum curve of low rank coal and its micro component

由表 1 可知,在 3 500 ~3 300 $cm^{-1}$ 附近为羟基的自缔合氢键吸收峰[14],低阶煤镜质组在附近的峰较宽,丝质组的吸收峰相对较小。3 种样品 3 000 ~ 2 750 $cm^{-1}$ 附近均有—$CH_3$、—$CH_2$ 基团吸收峰,属结构中 C—H 伸缩振动引起的。显微组分在 1 600 $cm^{-1}$ 的吸收峰差异明显,镜质组吸收峰较大,可能是 C ═ C(Ar)伸缩振动引起的,丝质组吸收峰可能是羧基 C ═ O 伸缩振动的贡献[15]。870 ~ 700 $cm^{-1}$ 附近有芳烃的 CH 基吸收峰和芳烃外面振动变形及苯环折褶振动的吸收峰。

## 2.2　低阶煤镜质组对炼焦煤膨胀性的影响

为表征低阶烟煤在配煤中的作用,尤其是软化熔融阶段对胶质体膨胀性的影响,在常规炼焦煤中添加不同比例的低阶烟煤镜质组,考察其膨胀性的变化规律,结果见表 3。

表 3　低阶烟煤镜质组对炼焦煤膨胀特性的影响

**Table 3　Effect of low rank coal vitrinite on coking coal expansion**

| 炼焦煤 | 镜质组比例/% | 特征温度/℃ | | | 温度间隔/℃ | 最大收缩度/% | 最大膨胀度/% |
|---|---|---|---|---|---|---|---|
| | | 软化 | 始膨胀 | 固化 | | | |
| 气煤 | 0 | 357.3 | 407.3 | 422.8 | 65.5 | 19.5 | 1.3 |
| | 2 | 355.4 | 419.3 | 425.6 | 70.2 | 21.5 | 0 |
| | 4 | 355.3 | 421.5 | 427.3 | 72.0 | 28.3 | -26.8 |
| | 8 | 356.8 | 424.2 | 428.9 | 72.1 | 20.6 | -19.5 |
| 肥煤 | 0 | 330.4 | 393.4 | 453.6 | 123.2 | 19.5 | 158.7 |
| | 2 | 337.8 | 396.7 | 451.9 | 114.1 | 20.7 | 135.7 |
| | 4 | 337.8 | 398.0 | 450.6 | 112.8 | 20.0 | 128.5 |
| | 8 | 346.4 | 401.2 | 449.8 | 103.4 | 19.7 | 88.2 |
| 焦煤 | 0 | 392.6 | 434.4 | 461.5 | 68.9 | 15.2 | 28.5 |
| | 2 | 393.3 | 440.2 | 463.9 | 70.6 | 17.3 | 10.8 |
| | 4 | 391.9 | 447.9 | 468.5 | 76.6 | 13.5 | -1.2 |
| | 8 | 388.9 | — | 457.4 | 68.5 | 10.3 | — |



由表 3 可知,添加 2% ~8% 的低阶烟煤镜质组对气煤、肥煤、焦煤的膨胀性影响差异较大。对于气煤和焦煤,由于开始软化温度稍有变小,使得塑性温度区间稍有增加,气煤增加约 7 ℃,焦煤增加约 10 ℃;肥煤塑性温度区间逐渐变小。收缩行为仅对肥煤的影响最小;随镜质组含量的增加,气煤最大收缩度略有增大,焦煤的最大收缩度呈减小趋势。镜质组对 3 种炼焦煤的膨胀度均有影响,随镜质组含量的增加,最大膨胀度减少,镜质组含量在 4% 以下时,对肥煤的影响相对较小,对焦煤和气煤的影响较大,甚至不膨胀。膨胀性大小反映了胶质体透气性强弱,配入低阶煤镜质组 3 种炼焦煤的胶质体透气性均增强,胶质体质量下降。

## 2.3　低阶煤镜质组对炼焦煤胶质体流动性的影响

为表征低阶烟煤在配煤中对胶质体流动性的影响,在常规炼焦煤中加入不同比例的低阶烟煤镜质组,其胶质体的流动性见表 4。由表 4 可知,低阶烟煤镜质组对气煤、肥煤和焦煤热塑性流动度的影响规律类似。随镜质组含量的增加,炼焦煤的软化熔融区间缩短,最大基氏流动度下降,对不同煤种影响程度不同。对于气煤,随低阶煤镜质组配入比例的增加,软化温度有增大趋势,固化温度几乎持平,最大流动度由 3 623 ddpm 降至 1 086 ddpm,基氏流动度曲线不断收窄,表明所得胶质体减少,流动性变差。低阶煤镜质组对肥煤影响相对较小,软化和固化温度区间变化不明显。镜质组对焦煤的影响程度

较气煤稍弱,镜质组配比为 12% 时,气煤配低阶煤镜质组的最大流动度下降 70.0%,肥煤配低阶煤镜质组最大流动度下降 66.1%,焦煤配低阶煤镜质组最大流动度下降了 78.4%。

表 4 低阶烟煤镜质组对炼焦煤流动性的影响

Table 4 Effect of low rank coal vitrinite on coking coal fluidity

| 炼焦煤 | 镜质组比例/% | 特征温度/℃ | | | 温度间隔/℃ | 最大流动度/ddpm |
|---|---|---|---|---|---|---|
| | | 软化 | 最大流动 | 固化 | | |
| 气煤 | 0 | 381 | 426 | 465 | 84 | 3 623 |
| | 2 | 383 | 426 | 465 | 82 | 2 786 |
| | 4 | 383 | 427 | 464 | 81 | 1 486 |
| | 8 | 387 | 430 | 466 | 79 | 1 156 |
| | 12 | 387 | 426 | 466 | 79 | 1 086 |
| 肥煤 | 0 | 369 | 441 | 483 | 114 | 29 868 |
| | 2 | 362 | 438 | 480 | 118 | 16 926 |
| | 4 | 370 | 433 | 478 | 108 | 21 216 |
| | 8 | 372 | 436 | 480 | 108 | 12 348 |
| | 12 | 366 | 435 | 478 | 112 | 10 121 |
| 焦煤 | 0 | 411 | 461 | 500 | 90 | 744 |
| | 2 | 411 | 482 | 498 | 87 | 404 |
| | 4 | 409 | 458 | 496 | 93 | 756 |
| | 8 | 409 | 464 | 499 | 90 | 281 |
| | 12 | 411 | 463 | 498 | 87 | 161 |

### 2.4 低阶煤镜质组对炼焦煤黏结特性的影响

通过对国标烟煤黏结指数测试方法的改进,在常规炼焦煤中分别配入 4%、8%、12% 的低阶烟煤镜质组,黏结力指数(*GI*)测定结果如图 2 所示。

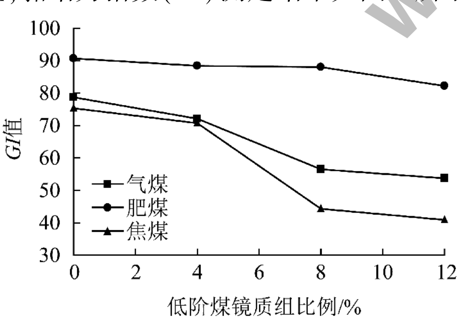


图 2 低阶煤镜质组对黏结特性的影响

Fig. 2 Effect of low rank coal vitrinite on caking property

由图 2 可知,随着配入低阶煤镜质组比例的增大,气煤、肥煤、焦煤的黏结力指数均下降。当低阶煤镜质组的比例为 12% 时,气煤、肥煤和焦煤的黏结力指数分别下降了 31.8%、9.4% 和 45.7%。低阶煤镜质组对炼焦煤黏结力指数的影响程度由大到小依次为焦煤、气煤、肥煤。低阶烟煤镜质组的加入与塑性胶质体的流动、膨胀和黏结特性并非线性关系,与肥煤的交互作用偏正,与气煤和焦煤的交互作用偏负。

## 3 结 论

1)低阶烟煤灰分较低,属不黏煤,其镜质组挥发分较原煤增加,且显示出弱黏结特性,*G* 值达到 43;而惰质组分的灰分较高,挥发分偏低,无黏结特征。配低阶煤镜质组比例为 12% 时,所得气煤配低阶煤镜质组的最大流动度由 3 623 ddpm 降至 1 086 ddpm,下降了 70.0%,黏结力指数 *GI* 由 78.7 降至 52.5,下降了 31.8%;所得肥煤配低阶煤镜质组的最大流动度由 29 868 ddpm 降至 10 121 ddpm,下降了 66.1%,黏结力指数 *GI* 由 90.7 降至 83.6,下降了 9.4%;所得焦煤配低阶煤镜质组的流动度由 744 ddpm 降至 161 ddpm,下降了 78.4%,黏结力指数 *GI* 由 75.3 降至 64.6,下降了 45.7%。配入低阶煤镜质组比例为 8% 时,气煤的膨胀度由 1.3% 降至-19.5%,肥煤的膨胀度由 158.7% 降至 88.2%,焦煤的膨胀度由 28.5% 降至-1.2%。

2)随着常规炼焦煤中低阶烟煤镜质组添加比例的增加,气煤、肥煤、焦煤等塑性胶质体的流动性、膨胀性和黏结力指数下降,存在劣化作用。但各指标变化规律并不存在线性关系,对焦煤影响最大,对肥煤影响较小。

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