**锂离子电池材料 粉末压实密度的测定**

**编**

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**说**

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（预审稿）

**2023年4月**

锂离子电池材料 粉末压实密度的测定

**（编制说明）**

**一、工作简况**

**1.1 任务来源**

根据国家标准化管理委员会《关于下达2021年第四批推荐性国家标准计划及相关标准外文版计划的通知》（国标委发[2021] 41号）的文件精神，国家标准《锂离子电池材料 粉末压实密度的测定》由全国有色金属标准化技术委员会负责归口，由全国有色金属标准化技术委员会粉末冶金分会执行，由厦门厦钨新能源材料股份有限公司、宁德时代新能源科技股份有限公司、元能科技（厦门）有限公司牵头起草。项目计划编号为20214500-T-610，项目计划完成时间为2023年12月。

**1.2 主起草单位简介**

厦门厦钨新能源材料股份有限公司是世界钨行业领军企业-厦门钨业股份有限公司的全资子公司。公司于2016年12月20日将新能源材料业务从厦门钨业母公司分立，设立厦门厦钨新能源材料有限公司（以下简称“厦钨新能源”）。2020年4月，在深入贯彻落实中央精神、全面落实深化国有企业改革的时代背景下，公司完成股份制改制，整体变更为厦门厦钨新能源材料股份有限公司。2021年8月，厦钨新能源充分抓住科创板分拆上市的契机，正式在上海证券交易所科创板挂牌上市（股票代码：688778），成为一家上市企业，是国内第五家、福建省第一家A拆A成功上市的公司，也是福建省首单分拆上市成功案例。公司现拥有8家全资、控股子公司，1家参股子公司，1所研究院，并设有海沧、海璟、三明、宁德、四川雅安（在建）五大生产基地，要把厦钨新能源建成最具国际竞争力的新能源材料产业基地。公司产品涵盖钴酸锂、镍钴锰酸锂材料、前驱体、磷酸铁锂、高镍材料、NCA等全系列新能源材料产品，积极进行富锂锰基、5V高电压、磷酸盐材料、固态电池等下一代新能源材料产品开发，不断取得技术新突破。

宁德时代新能源科技股份有限公司成立于2011年，其专注于新能源汽车动力电池系统、储能系统的研发、生产和销售，致力于为全球新能源应用提供一流解决方案。核心技术为动力和储能电池领域，材料、电芯、电池系统、电池回收二次利用等全产业链的研发及制造能力,公司于2018年在深交所创业板上市。

元能科技是一家专业从事锂离子电池检测仪器研发和生产的高科技企业。公司侧重技术的研究和储备,保持大额度研发投入，创建了一支由博士、硕士和行业专家等组成的经验丰富、技术精湛的研发团队，在仪器检测与分析技术领域开展了卓有成效的研究开发工作，申请了多项发明专利和实用新型专利。元能科技和厦门大学、中国科学院、宁德时代新能源科技股份有限公司等多个单位或企业展开科技成果项目的技术合作与产业化。

**1.3 主要起草单位和工作组成员及其工作**

本文件起草单位有：厦门厦钨新能源材料股份有限公司、宁德时代新能源科技股份有限公司、元能科技 （厦门）有限公司、宁德新能源科技有限公司等。

其中厦门厦钨新能源材料股份有限公司负责样品的收集和分发，分析方法的实验研究，样品测试结果的收集和处理，试验报告和编制说明的撰写。宁德时代新能源科技股份有限公司负责分析方法的实验研究与讨论以及一、二验工作。元能科技 （厦门）有限公司负责分析方法的实验研究与讨论，标准文件的撰写。宁德新能源科技有限公司、宁波容百新能源科技股份有限公司、成都巴莫科技有限责任公司、广东邦普循环科技有限公司、巴斯夫杉杉电池材料有限公司、福建紫金锂元材料科技有限公司、浙江友山新材料有限公司、湖南长远锂科股份有限公司、湖北万润新能源科技股份有限公司、北京当升材料科技股份有限公司、元能科技（厦门）有限公司为一验单位，负责对试验报告中的试验过程参数进行填写、提供材料压实密度的测试数据，并对标准文本提出修改意见。宁德时代新能源科技股份有限公司、宁波容百新能源科技有限公司、江门市科恒实业股份有限公司、格林美（无锡）能源材料有限公司、中伟新材料股份有限公司、浙江巴莫科技有限责任公司、成都巴莫科技有限责任公司、四川赛科检测技术有限公司、宜宾锂宝新材料有限公司、浙江友山新材料有限公司、湖北万润新能源科技股份有限公司、福安青美能源材料有限公司、北京当升材料科技股份有限公司、深圳中芯能科技有限公司、元能科技（厦门）有限公司、深圳市德方创域新能源科技有限公司、深圳市德方纳米科技股份有限公司为二验单位，负责对试验报告中的试验过程参数进行填写、提供材料压实密度的测试数据。本文件样品收集过程中，福建紫金锂元材料科技有限公司、北京当升材料科技股份有限公司、广东邦普循环科技有限公司、华友新能源科技（衢州）有限公司、湖北万润新能源科技股份有限公司负责提供钴酸锂、磷酸铁锂等材料样品。

本文件主要起草人有：XXX、XXX、XXX……。

各起草人在本文件编制过程中的工作职责见表1所示：

表1 各起草人及其工作职责

|  |  |
| --- | --- |
| 起草人姓名 | 工作职责 |
| （各单位提供起草人信息） | 负责样品收集、标准文本起草、标准编制说明撰写，意见汇总处理，参加标准讨论和审定会议 |
| （各单位提供起草人信息） | 负责对试验方案和试验条件进行验证，对标准技术内容进行审核，参加标准工作会议等 |
| （各单位提供起草人信息） | 提供测试数据；对标准文本提出修改意见 |

**1.4 主要工作过程**

厦门厦钨新能源材料股份有限公司、宁德时代新能源科技股份有限公司、元能科技 （厦门）有限公司在接到本文件制订任务后，立即组织骨干人员成立了标准编制组，制定了该标准的研究内容、技术路线、任务分工和进度安排。主要工作过程经历以下阶段：

**1.4.1立项阶段**

2020年11月，厦门厦钨新能源材料股份有限公司、宁德时代新能源科技股份有限公司、元能科技 （厦门）有限公司向全国有色金属标准化技术委员会粉末冶金分会(SAC/TC243/SC4)提交国家标准《锂离子电池材料 粉末压实密度的测定》项目建议书。

2021年12月31日，国家标准化管理委员会印发《关于下达2021年第四批推荐性国家标准计划及相关标准外文版计划的通知》（国标委发[2021] 41号），国家标准《锂离子电池材料 粉末压实密度的测定》立项成功。

**1.4.2 起草阶段**

2022年5月至2022年9月，厦门厦钨新能源材料股份有限公司、宁德时代新能源科技股份有限公司、元能科技 （厦门）有限公司接到《锂离子电池材料 粉末压实密度的测定》起草编制工作任务后，成立了标准编制工作组，展开了标准讨论稿和编制说明的工作分配及实施工作计划等事项。本文件在起草过程中，工作组对国际和国外标准进行了查新、收集、分析，研究了相关技术资料，对该测定方法进行了多次验证实验，最终形成了标准讨论稿和编制说明。

2022年5月7日，全国有色金属标准化技术委员会召开网络工作会议，会议对《锂离子电池材料 粉末压实密度的测定》进行了任务落实。2022年11月，标准编制组向各参编单位发送标准文本和试验条件调研表，对标准中涉及的技术参数和试验方法开展了调研，形成了试验方案并组织了第一次验证试验，对影响测试的几个参数，压强、测试模式、称样量、模具直径等进行摸底验证。2023年3月，工作组将一验数据进行汇总分析并和参与单位进行交流，确认了二验的方案。2023年3月至4月，工作组展开第二次试验并对数据进行分析汇总。

**1.4.3 征求意见阶段**

2022年9月20日，全国有色金属标准化技术委员会在山西太原召开工作会议。多家单位的代表对《锂离子电池材料 粉末压实密度的测定》的标准讨论稿和编制说明进行了仔细认真的讨论，并提出了修改意见和建议（详见《标准征求意见稿意见汇总处理表》）。2023年3月7日，标准编制组组织了本文件的网络讨论会。会议中各单位代表就国家标准讨论稿和编制说明进行讨论。2023年4月，标准编制组根据各家单位提出的意见，对标准文本和编制说明进行修改，同时对试验数据进行补充，形成预审稿。2023年4月26日，全国有色金属标准化技术委员会在湖北武汉召开工作会议。多家单位代表对《锂离子电池材料 粉末压实密度的测定》的预审稿提出修改意见（详见《标准征求意见稿意见汇总处理表》）。

**1.4.4 审查阶段**

……。

**1.4.5 报批阶段**

……。

**二、标准编制原则**

**2.1 符合性**

1、本文件按 GB/T 1.1-2020《 标准化工作导则 第 1 部分：标准的结构和编写规则》要求编写。

2、本文件的试验方法以满足国内锂离子电池正极材料的实际生产、使用需要为原则，提高标准的普适性。

**2.2 适用性和先进性**

锂离子电池材料粉末压实密度测试方法标准的缺失和不足，导致相关上下游企业对粉末压实密度的测试手段与方法不统一，各家企业测得的数据结果不一致，极大地增加了相关企业的品质监控和来料检验的难度。由于测试方法间的误差导致部分粉末压实密度异常的材料流入正常电池制作流程，造成制成的极片异常，极大地影响电池性能，增加生产周期及不良率，导致运营成本增加。综上所述，随着市场对锂离子电池需求的快速增长，势必要建立更多标准以促进行业的规范发展和健康壮大。因此锂离子电池粉末压实密度测定方法的标准化是必要且紧迫的。

本文件提出了一种测试锂电正极材料压实密度的方法，包括明确了压实密度测试的几种形式以及关键的控制参数来减小测试误差，提高数据准确性和稳定性。本文件的建立会使得锂电行业对粉末压实密度的测试方法形成统一的标准，进而提高测试结果的可靠性，极大的减少了由于企业间对标而产生的时间及金钱的浪费，减少了因数据偏差而导致的争端。

**三、确定标准主要内容的依据**

**3.1**  标准主要内容的依据

GB/T 24533-2019《锂离子电池石墨类负极材料》国家标准于2019年3月25日发布，2020年2月1日实施，该文件中规定了石墨类负极材料压实密度测定的基本要求，该文件的5.2理化指标中针对石墨负极材料提出了压实密度的技术指标要求；文件中的6.1.6针对压实密度技术指标要求提出了试验方法。相较于标准 GB/T 24533-2019，本文件的测试方法针对相对全面的锂离子电池材料粉末，科学地引入了标准压力、压强、加压压实密度、卸压压实密度等几个重要参数。

**3.2 标准主要内容说明**

本文件正文部分共分为 10 章，其中第 1、 2、 3 章为规范性一般要素，包括范围、规范性引用文件、术语和定义，第 4、 5、 6、 7、 8、 9 、10章为规范性技术要素。第 1 章范围：本文件规定了镍钴锰酸锂、镍锰酸锂、磷酸铁锂、磷酸锰铁锂、钴酸锂、锰酸锂等锂离子材料的粉末压实密度测定方法，适用于镍钴锰酸锂、镍锰酸锂、磷酸铁锂、磷酸锰铁锂、钴酸锂、锰酸锂等锂离子材料压实密度的测定。

第2、3章分别为规范性引用文件、术语和定义，按照最新修订的 GB/T 1.1-2020《标准化工作导则 第 1 部分：标准化文件的结构和起草规则》的要求，保留了相关章节。

第4章 方法原理，规定了本文中第8章试验步骤的方法，明确测试原理及相关计算要求，进一步明确了测试过程的关键影响因子。

第5章 试剂和材料，规定了本文件第8章节需要用到的各种试剂和材料。

第6章 仪器设备，规定了本文件第8章试验步骤章节需要用到的关键设备和装置清单，所述设备和装置本文件中出现的先后顺序列出，便于前后对照。本章节只列出了涉及测试内容和步骤的关键设备，确保标准的适用性。

第7章 样品，对待测样品的状态进行了规定。

第8章 试验步骤，规定了本文件中压实密度测定的三种模式以及关键测试参数的设置、测试流程及关键点，本章节是按照前期验证结果的普适性进行规定与明确，重点关注测试参数的合理性，数据的全面性。是本文件中核心章节，关注试验步骤的科学性、规范性、可操作性，对于可能引起重大分歧不宜给出特别具体的参数要求的步骤条款，本章节以给出范围和规定过程要求进行处理。

第9章 试验结果计算及数据处理，详细列出压实密度的计算公式、测试次数以及修约规则。

第10章 试验报告，规定了报告所包含的必备要求内容，包括样品名称、测试日期、测试人员、试验条件、分析结果与表示方法、在测定中观察到的异常现象及任何不包括在本文件中的操作或是自由选择的试验条件。

**3.3 主要试验验证情况**

**3.3.1 试样选取**

锂离子电池材料粉末产品种类有很多，包含镍钴锰酸锂、镍锰酸锂、磷酸铁锂、磷酸锰铁锂、钴酸锂、锰酸锂、富锂等，其中每一种又可以按照元素比例、粒度、比表面积、形貌、振实密度、容量、循环寿命等参数进行分类，不同特性参数的产品适用于不同的领域。譬如磷酸铁锂以粒度比例为分类指标，通常粒度较小的磷酸铁锂产品多用于电容器或有高功率需求领域，中等粒度的磷酸铁锂产品主要用于小动力、数码及电动自行车，大颗粒或者级配产品主要用于有高能量密度需求的领域，如电动汽车、储能等，又如镍钴锰酸锂材料以元素比例分，可含有1:1:1系列、5:2:3系列、8:1:1系列等等。样品类型会影响测试参数的选择，因此在验证阶段的选样要综合考虑样品的代表性。

表2 一验材料的选择

|  |  |  |
| --- | --- | --- |
| 编号 | 种类 | D50(μm) |
| 样品1 | 镍钴锰酸锂 | 7.489 |
| 样品2 | 镍钴锰酸锂 | 16.483 |
| 样品3 | 镍钴锰酸锂 | 3.911 |
| 样品4 | 钴酸锂 | 14.844 |
| 样品5 | 磷酸铁锂 | 4.658 |

表3 二验材料的选择

|  |  |
| --- | --- |
| 样品编号 | 样品种类 |
| 样品1 | 磷酸铁锂 |
| 样品2 | 磷酸铁锂 |
| 样品3 | 磷酸锰铁锂 |
| 样品4 | 磷酸锰铁锂 |
| 样品5 | 镍钴锰酸锂 |
| 样品6 | 镍钴锰酸锂 |
| 样品7 | 镍钴锰酸锂 |
| 样品8 | 镍钴锰酸锂 |
| 样品9 | 镍钴锰酸锂 |
| 样品10 | 钴酸锂 |
| 样品11 | 钴酸锂 |
| 样品12 | 钴酸锂 |
| 样品13 | 磷酸铁锂 |
| 样品14 | 磷酸铁锂 |

**3.3.2 关键参数**

表4 关键参数验证

|  |  |  |  |
| --- | --- | --- | --- |
|  | 测试模式 | 压强范围 | 卸压压力 |
| 1 | 自动加压模式 | 63.32~339.20 MPa | / |
| 2 | 自动卸压模式 | 63.32~339.20 MPa | 5 MPa |
| 3 | 手动模式 | 63.32~339.20 MPa | 完全卸压 |

**3.3.3 试验方案**

按照以下实验步骤进行方法验证

1. 按实验要求称取试料，精确至±0.005g
2. 采用蘸有乙醇的无尘纸清洁模具，包括内腔及上下垫片，以无尘纸无肉眼可见污渍为标准，将清洁后的模具放入粉末压实密度测试系统加压腔室内。
3. 试料测试前需开启设备，进行预先检查与验证。
4. 试料测定前需进行参数配置（手动加压设备无需此步骤）
5. 称取的试料置于已含下垫片的测试模具中，确保样品均摊于模具内腔，轻轻装入上垫片，将已加好试料的模具放入测试腔内。手动加压设备加试料前需连同上下垫片及下端子进行初始厚度测量，记为H1。
6. 结合参数设定施加压强及保压时间（保压时间本次实验设定为30秒），自动或手动垂直于测试面施加试验力。
7. 加压完成厚度测量，若为集成一体化测试系统，直接软件端自动采集厚度，若为手动采集，则需连同下端子一起将含样品的测试模具取出，测量施压后总体厚度，厚度记为H2。
8. 自动输出压实密度数据可直接结合数据进行分析，若为手动厚度采集，按照以下公式计算粉末压实密度。

式中，

ρ—压实密度，单位为克每立方厘米（g/cm3）

m—样品质量，单位为克（g）

d—模具的直径，单位为厘米（cm）

H2—加试料压实后综合测量厚度，单位为厘米（cm）

H1—加试料前测量厚度，单位为厘米（cm）

按照如上方法进行方法验证，每个样品重复测试3次并记录相关数据。

**实验一：加压测试条件下样品测试（自动）**

选取内径为13mm或其他尺寸的模具为测试模具，按“加料量选择”进行称重并按实验步骤操作，在加压条件下测试“压强选择”序号1~6号对应压强下的材料压实密度进行测量并记录。

**实验二：卸压测试条件下样品测试（自动）**

选取内径为13mm或其他尺寸的模具为测试模具，按“加料量选择”进行称重并按实验步骤操作，在卸压（卸压压强为5Mpa，即666.4N，68kg）条件下测试“压力选择”序号1~6号对应压强下的材料压实密度进行测量并记录。

**实验三：卸压测试条件下样品测试（手动）**

选取内径为13mm或其他尺寸的模具为测试模具，按“加料量选择”进行称重并按实验步骤操作，在卸压（移出手动测量）条件下测试“压力选择”序号1~6号对应压强下的材料压实密度进行测量并记录。

表5 加料量选择

|  |  |  |
| --- | --- | --- |
| 模具内径/mm | 镍钴锰酸锂&钴酸锂 | 铁锂/锰铁锂 |
| 13 | 1.5g | 0.6g |
| 16 | 2.0g | 1.0g |
| 其他直径尺寸可结合实际情况，选取加料量 | | |

表6 样品的压力选择

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 压力选择（压力压强换算表格）-13mm-铁锂/锰铁锂 | | | | | |
| 序号 | 压力/N | 最大压力/kg | 最大压力/T | 模具内径/mm | 压强/MPa |
| 1 | 8400 | 857.14 | 0.86 | 13 | 63.32 |
| 2 | 15000 | 1530.61 | 1.53 | 13 | 113.07 |
| 3 | 20000 | 2040.82 | 2.04 | 13 | 150.76 |
| 4 | 25000 | 2551.02 | 2.55 | 13 | 188.44 |
| 5 | 26500 | 2704.08 | 2.70 | 13 | 199.75 |
| 6 | 30000 | 3061.22 | 3.06 | 13 | 226.13 |
| 压力选择（压力压强换算表格）-13mm-镍钴锰酸锂 | | | | | |
| 序号 | 压力/N | 最大压力/kg | 最大压力/T | 模具直径/mm | 压强/MPa |
| 1 | 8400 | 857.14 | 0.86 | 13 | 63.32 |
| 2 | 20000 | 2040.82 | 2.04 | 13 | 150.76 |
| 3 | 25000 | 2551.02 | 2.55 | 13 | 188.44 |
| 4 | 26500 | 2704.08 | 2.70 | 13 | 199.75 |
| 5 | 40000 | 4081.63 | 4.08 | 13 | 301.51 |
| 6 | 45000 | 4591.84 | 4.59 | 13 | 339.20 |
| 压力选择（压力压强换算表格）-13mm-钴酸锂 | | | | | |
| 序号 | 压力/N | 最大压力/kg | 最大压力/T | 模具直径/mm | 压强/MPa |
| 1 | 8400 | 857.14 | 0.86 | 13 | 63.32 |
| 2 | 20000 | 2040.82 | 2.04 | 13 | 150.76 |
| 3 | 25000 | 2551.02 | 2.55 | 13 | 188.44 |
| 4 | 26500 | 2704.08 | 2.70 | 13 | 199.75 |
| 5 | 40000 | 4081.63 | 4.08 | 13 | 301.51 |
| 6 | 45000 | 4591.84 | 4.59 | 13 | 339.20 |

**3.3.4 试验原始数据**

实验一：加压测试条件下样品测试（自动）

如表7所示是不同实验室针对不同样品进行的压实密度测试的原始数据。同一实验室内，在各个压强下，三次测试结果的重复性较好。除个别实验室外，变异系数（COV）在1%以内。

表7实验一条件下各实验室的压实密度原始数据（g/cm3）

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| G | 样品1 | 1 | 2.078 | 2.229 | | 2.317 | | 2.401 | | 2.414 | | 2.465 | |
| 2 | 2.082 | 2.234 | | 2.323 | | 2.395 | | 2.421 | | 2.472 | |
| 3 | 2.080 | 2.220 | | 2.319 | | 2.391 | | 2.417 | | 2.468 | |
| 均值 | 2.080 | 2.227 | | 2.320 | | 2.396 | | 2.417 | | 2.468 | |
| COV | 0.08% | 0.25% | | 0.10% | | 0.18% | | 0.11% | | 0.11% | |
| H-1 | 样品1 | 1 | 2.060 | 2.240 | | 2.360 | | 2.470 | | 2.500 | | 2.580 | |
| 2 | 2.070 | 2.250 | | 2.360 | | 2.470 | | 2.500 | | 2.570 | |
| 3 | 2.080 | 2.260 | | 2.380 | | 2.490 | | 2.510 | | 2.590 | |
| 均值 | 2.070 | 2.250 | | 2.367 | | 2.477 | | 2.503 | | 2.580 | |
| COV | 0.39% | 0.36% | | 0.40% | | 0.38% | | 0.19% | | 0.32% | |
| H-2 | 样品1 | 1 | 2.040 | 2.220 | | 2.330 | | 2.440 | | 2.470 | | 2.540 | |
| 2 | 2.070 | 2.250 | | 2.360 | | 2.470 | | 2.500 | | 2.570 | |
| 3 | 2.080 | 2.260 | | 2.380 | | 2.480 | | 2.510 | | 2.590 | |
| 均值 | 2.063 | 2.243 | | 2.357 | | 2.463 | | 2.493 | | 2.567 | |
| COV | 0.82% | 0.76% | | 0.87% | | 0.69% | | 0.68% | | 0.80% | |
| E | 样品1 | 1 | 2.110 | 2.260 | | 2.360 | | 2.430 | | 2.470 | | 2.530 | |
| 2 | 2.130 | 2.280 | | 2.380 | | 2.450 | | 2.490 | | 2.540 | |
| 3 | 2.130 | 2.280 | | 2.380 | | 2.460 | | 2.490 | | 2.540 | |
| 均值 | 2.123 | 2.273 | | 2.373 | | 2.447 | | 2.483 | | 2.537 | |
| COV | 0.44% | 0.41% | | 0.40% | | 0.51% | | 0.38% | | 0.19% | |
| C | 样品1 | 1 | 2.030 | 2.160 | | 2.230 | | 2.290 | | 2.300 | | / | |
| 2 | 2.030 | 2.160 | | 2.230 | | 2.290 | | 2.300 | | / | |
| 3 | 2.030 | 2.160 | | 2.230 | | 2.290 | | 2.300 | | / | |
| 均值 | 2.030 | 2.160 | | 2.230 | | 2.290 | | 2.300 | | / | |
| COV | 0.00% | 0.00% | | 0.00% | | 0.00% | | 0.00% | | / | |
| T | 样品1 | 1 | 1.996 | 2.115 | | 2.180 | | 2.235 | | 2.247 | | 2.282 | |
| 2 | 2.011 | 2.133 | | 2.199 | | 2.253 | | 2.266 | | 2.300 | |
| 3 | 2.006 | 2.127 | | 2.194 | | 2.248 | | 2.261 | | 2.295 | |
| 均值 | 2.004 | 2.125 | | 2.191 | | 2.245 | | 2.258 | | 2.293 | |
| COV | 0.31% | 0.35% | | 0.35% | | 0.35% | | 0.36% | | 0.33% | |
| A | 样品1 | 1 | 2.262 | 2.388 | | 2.456 | | 2.515 | | 2.551 | | 2.585 | |
| 2 | 2.266 | 2.388 | | 2.462 | | 2.522 | | 2.551 | | 2.587 | |
| 3 | 2.262 | 2.392 | | 2.460 | | 2.519 | | 2.554 | | 2.592 | |
| 均值 | 2.263 | 2.389 | | 2.459 | | 2.519 | | 2.552 | | 2.588 | |
| COV | 0.08% | 0.08% | | 0.10% | | 0.11% | | 0.06% | | 0.11% | |
| V-1 | 样品1 | 1 | 1.991 | 2.104 | | 2.164 | | 2.212 | | 2.223 | | 2.252 | |
| 2 | 1.991 | 2.102 | | 2.161 | | 2.209 | | 2.219 | | 2.248 | |
| 3 | 1.989 | 2.100 | | 2.159 | | 2.207 | | 2.218 | | 2.247 | |
| 均值 | 1.990 | 2.102 | | 2.161 | | 2.209 | | 2.220 | | 2.249 | |
| COV | 0.04% | 0.08% | | 0.10% | | 0.10% | | 0.10% | | 0.11% | |
| V-2 | 样品1 | 1 | 1.991 | 2.160 | | 2.267 | | 2.366 | | 2.393 | | 2.461 | |
| 2 | 1.990 | 2.157 | | 2.263 | | 2.362 | | 2.388 | | 2.456 | |
| 3 | 1.989 | 2.155 | | 2.261 | | 2.360 | | 2.387 | | 2.455 | |
| 均值 | 1.990 | 2.157 | | 2.263 | | 2.363 | | 2.389 | | 2.457 | |
| COV | 0.04% | 0.08% | | 0.11% | | 0.11% | | 0.11% | | 0.12% | |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| G | 样品3 | 1 | 2.177 | 2.329 | | 2.427 | | 2.506 | | 2.533 | | 2.590 | |
| 2 | 2.169 | 2.332 | | 2.417 | | 2.509 | | 2.523 | | 2.578 | |
| 3 | 2.178 | 2.331 | | 2.429 | | 2.508 | | 2.534 | | 2.577 | |
| 均值 | 2.174 | 2.331 | | 2.424 | | 2.508 | | 2.530 | | 2.582 | |
| COV | 0.19% | 0.04% | | 0.22% | | 0.04% | | 0.20% | | 0.23% | |
| H-1 | 样品3 | 1 | 2.220 | 2.390 | | 2.510 | | 2.640 | | 2.670 | | 2.750 | |
| 2 | 2.220 | 2.400 | | 2.510 | | 2.630 | | 2.660 | | 2.740 | |
| 3 | 2.210 | 2.390 | | 2.510 | | 2.650 | | 2.670 | | 2.750 | |
| 均值 | 2.217 | 2.393 | | 2.510 | | 2.640 | | 2.667 | | 2.747 | |
| COV | 0.21% | 0.20% | | 0.00% | | 0.31% | | 0.18% | | 0.17% | |
| H-2 | 样品3 | 1 | 2.200 | 2.400 | | 2.530 | | 2.650 | | 2.680 | | 2.760 | |
| 2 | 2.180 | 2.370 | | 2.500 | | 2.620 | | 2.650 | | 2.730 | |
| 3 | 2.200 | 2.400 | | 2.520 | | 2.650 | | 2.680 | | 2.760 | |
| 均值 | 2.193 | 2.390 | | 2.517 | | 2.640 | | 2.670 | | 2.750 | |
| COV | 0.43% | 0.59% | | 0.50% | | 0.54% | | 0.53% | | 0.51% | |
| E | 样品3 | 1 | 2.22 | 2.37 | | 2.48 | | 2.56 | | 2.59 | | 2.64 | |
| 2 | 2.22 | 2.37 | | 2.47 | | 2.56 | | 2.59 | | 2.63 | |
| 3 | 2.20 | 2.36 | | 2.46 | | 2.55 | | 2.58 | | 2.64 | |
| 均值 | 2.213 | 2.367 | | 2.470 | | 2.557 | | 2.587 | | 2.637 | |
| COV | 0.43% | 0.20% | | 0.33% | | 0.18% | | 0.18% | | 0.18% | |
| T | 样品3 | 1 | 2.082 | 2.203 | | 2.272 | | 2.328 | | 2.342 | | 2.377 | |
| 2 | 2.083 | 2.199 | | 2.265 | | 2.322 | | 2.332 | | 2.370 | |
| 3 | 2.136 | 2.252 | | 2.318 | | 2.374 | | 2.386 | | 2.422 | |
| 均值 | 2.100 | 2.218 | | 2.285 | | 2.341 | | 2.353 | | 2.390 | |
| COV | 1.20% | 1.09% | | 1.03% | | 0.98% | | 1.00% | | 0.97% | |
| C | 样品3 | 1 | 2.100 | 2.230 | | 2.300 | | 2.350 | | 2.370 | | / | |
| 2 | 2.100 | 2.230 | | 2.300 | | 2.360 | | 2.370 | | / | |
| 3 | 2.110 | 2.240 | | 2.300 | | 2.360 | | 2.380 | | / | |
| 均值 | 2.103 | 2.233 | | 2.300 | | 2.357 | | 2.373 | | / | |
| COV | 0.22% | 0.21% | | 0.00% | | 0.20% | | 0.20% | | / | |
| V-2 | 样品3 | 1 | 2.065 | 2.231 | | 2.342 | | 2.446 | | 2.472 | | 2.547 | |
| 2 | 2.064 | 2.228 | | 2.336 | | 2.438 | | 2.465 | | 2.534 | |
| 3 | 2.064 | 2.228 | | 2.336 | | 2.438 | | 2.465 | | 2.534 | |
| 均值 | 2.064 | 2.229 | | 2.338 | | 2.440 | | 2.468 | | 2.538 | |
| COV | 0.03% | 0.07% | | 0.12% | | 0.15% | | 0.14% | | 0.24% | |
| V-1 | 样品3 | 1 | 2.065 | 2.172 | | 2.232 | | 2.282 | | 2.292 | | 2.324 | |
| 2 | 2.064 | 2.169 | | 2.227 | | 2.275 | | 2.285 | | 2.313 | |
| 3 | 2.063 | 2.169 | | 2.226 | | 2.273 | | 2.284 | | 2.312 | |
| 均值 | 2.064 | 2.170 | | 2.228 | | 2.277 | | 2.287 | | 2.316 | |
| COV | 0.03% | 0.07% | | 0.12% | | 0.16% | | 0.15% | | 0.22% | |
| A | 样品3 | 1 | 2.387 | 2.523 | | 2.601 | | 2.665 | | 2.698 | | 2.733 | |
| 2 | 2.402 | 2.526 | | 2.607 | | 2.688 | | 2.709 | | 2.747 | |
| 3 | 2.389 | 2.521 | | 2.598 | | 2.661 | | 2.693 | | 2.731 | |
| 均值 | 2.393 | 2.523 | | 2.602 | | 2.671 | | 2.700 | | 2.737 | |
| COV | 0.28% | 0.08% | | 0.14% | | 0.45% | | 0.25% | | 0.26% | |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| R | 样品4 | 1 | 1.953 | 2.046 | | 2.141 | | 2.227 | | 2.237 | | 2.312 | |
| 2 | 1.934 | 2.032 | | 2.139 | | 2.220 | | 2.268 | | 2.257 | |
| 3 | 1.948 | 2.017 | | 2.142 | | 2.235 | | 2.273 | | 2.291 | |
| 均值 | 1.945 | 2.032 | | 2.141 | | 2.227 | | 2.260 | | 2.286 | |
| COV | 0.42% | 0.59% | | 0.07% | | 0.27% | | 0.70% | | 0.99% | |
| P | 样品4 | 1 | 2.172 | 2.319 | | 2.407 | | 2.489 | | 2.532 | | 2.573 | |
| 2 | 2.178 | 2.325 | | 2.417 | | 2.506 | | 2.537 | | 2.585 | |
| 3 | 2.168 | 2.316 | | 2.410 | | 2.490 | | 2.529 | | 2.575 | |
| 均值 | 2.173 | 2.320 | | 2.411 | | 2.495 | | 2.532 | | 2.578 | |
| COV | 0.21% | 0.15% | | 0.17% | | 0.32% | | 0.14% | | 0.20% | |
| T | 样品4 | 1 | 2.060 | 2.174 | | 2.240 | | 2.294 | | 2.308 | | 2.341 | |
| 2 | 2.095 | 2.214 | | 2.283 | | 2.341 | | 2.354 | | 2.388 | |
| 3 | 2.052 | 2.165 | | 2.230 | | 2.281 | | 2.294 | | 2.325 | |
| 均值 | 2.069 | 2.184 | | 2.251 | | 2.305 | | 2.319 | | 2.352 | |
| COV | 0.92% | 0.98% | | 1.01% | | 1.11% | | 1.10% | | 1.14% | |
| N | 样品4 | 1 | 2.079 | 2.190 | | 2.256 | | 2.310 | | 2.321 | | 2.357 | |
| 2 | 2.079 | 2.192 | | 2.257 | | 2.311 | | 2.322 | | 2.359 | |
| 3 | 2.081 | 2.195 | | 2.261 | | 2.317 | | 2.327 | | 2.364 | |
| 均值 | 2.080 | 2.193 | | 2.258 | | 2.313 | | 2.323 | | 2.360 | |
| COV | 0.04% | 0.09% | | 0.10% | | 0.12% | | 0.11% | | 0.13% | |
| D | 样品4 | 1 | 2.086 | 2.206 | | 2.273 | | 2.330 | | 2.342 | | 2.379 | |
| 2 | 2.096 | 2.215 | | 2.281 | | 2.337 | | 2.350 | | 2.386 | |
| 3 | 2.093 | 2.211 | | 2.277 | | 2.333 | | 2.345 | | 2.381 | |
| 均值 | 2.092 | 2.211 | | 2.277 | | 2.333 | | 2.346 | | 2.382 | |
| COV | 0.19% | 0.16% | | 0.15% | | 0.14% | | 0.14% | | 0.13% | |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| G | 样品5 | 1 | 3.146 | | 3.510 | | 3.632 | | 3.667 | | 3.930 | | 4.012 |
| 2 | 3.135 | | 3.496 | | 3.606 | | 3.640 | | 3.897 | | 3.978 |
| 3 | 3.141 | | 3.492 | | 3.613 | | 3.647 | | 3.907 | | 3.988 |
| 均值 | 3.141 | | 3.499 | | 3.617 | | 3.651 | | 3.911 | | 3.993 |
| COV | 0.14% | | 0.22% | | 0.30% | | 0.32% | | 0.35% | | 0.36% |
| H-1 | 样品5 | 1 | 3.150 | | 3.570 | | 3.720 | | 3.760 | | 4.100 | | 4.220 |
| 2 | 3.140 | | 3.550 | | 3.700 | | 3.740 | | 4.080 | | 4.200 |
| 3 | 3.120 | | 3.530 | | 3.670 | | 3.720 | | 4.050 | | 4.170 |
| 均值 | 3.137 | | 3.550 | | 3.697 | | 3.740 | | 4.077 | | 4.197 |
| COV | 0.40% | | 0.46% | | 0.56% | | 0.44% | | 0.50% | | 0.49% |
| H-2 | 样品5 | 1 | 3.112 | | 3.524 | | 3.669 | | 3.711 | | 4.051 | | 4.172 |
| 2 | 3.110 | | 3.520 | | 3.670 | | 3.710 | | 4.050 | | 4.170 |
| 3 | 3.120 | | 3.540 | | 3.680 | | 3.720 | | 4.070 | | 4.190 |
| 均值 | 3.114 | | 3.528 | | 3.673 | | 3.714 | | 4.057 | | 4.177 |
| COV | 0.14% | | 0.24% | | 0.14% | | 0.12% | | 0.23% | | 0.22% |
| H-3 | 样品5 | 1 | 3.080 | | 3.500 | | 3.650 | | 3.690 | | 4.030 | | 4.150 |
| 2 | 3.080 | | 3.490 | | 3.630 | | 3.670 | | 4.010 | | 4.130 |
| 3 | 3.140 | | 3.560 | | 3.700 | | 3.750 | | 4.080 | | 4.200 |
| 均值 | 3.100 | | 3.517 | | 3.660 | | 3.703 | | 4.040 | | 4.160 |
| COV | 0.91% | | 0.88% | | 0.80% | | 0.92% | | 0.73% | | 0.71% |
| H-4 | 样品5 | 1 | 3.080 | | 3.490 | | 3.630 | | 3.670 | | 4.010 | | 4.130 |
| 2 | 3.080 | | 3.490 | | 3.630 | | 3.670 | | 4.010 | | 4.130 |
| 3 | 3.060 | | 3.470 | | 3.610 | | 3.650 | | 3.990 | | 4.110 |
| 均值 | 3.073 | | 3.483 | | 3.623 | | 3.663 | | 4.003 | | 4.123 |
| COV | 0.31% | | 0.27% | | 0.26% | | 0.26% | | 0.24% | | 0.23% |
| E | 样品5 | 1 | 3.120 | | 3.470 | | 3.590 | | 3.650 | | 3.870 | | 3.960 |
| 2 | 3.120 | | 3.470 | | 3.600 | | 3.660 | | 3.870 | | 3.970 |
| 3 | 3.120 | | 3.480 | | 3.610 | | 3.660 | | 3.870 | | 3.960 |
| 均值 | 3.120 | | 3.473 | | 3.600 | | 3.657 | | 3.870 | | 3.963 |
| COV | 0.00% | | 0.14% | | 0.23% | | 0.13% | | 0.00% | | 0.12% |
| Q | 样品5 | 1 | 3.141 | | 3.495 | | 3.574 | | 3.583 | | 3.798 | | 3.885 |
| 2 | 3.136 | | 3.517 | | 3.559 | | 3.593 | | 3.800 | | 3.875 |
| 3 | 3.140 | | 3.482 | | 3.565 | | 3.590 | | 3.809 | | 3.879 |
| 均值 | 3.139 | | 3.498 | | 3.566 | | 3.589 | | 3.802 | | 3.880 |
| COV | 0.07% | | 0.41% | | 0.17% | | 0.12% | | 0.13% | | 0.11% |
| C | 样品5 | 1 | 3.130 | | 3.480 | | 3.580 | | 3.610 | | / | | / |
| 2 | 3.130 | | 3.470 | | 3.580 | | 3.610 | | / | | / |
| 3 | 3.130 | | 3.480 | | 3.580 | | 3.610 | | / | | / |
| 均值 | 3.130 | | 3.477 | | 3.580 | | 3.610 | | / | | / |
| COV | 0.00% | | 0.14% | | 0.00% | | 0.00% | | / | | / |
| V-1 | 样品5 | 1 | 3.047 | | 3.338 | | 3.421 | | 3.441 | | 3.600 | | 3.647 |
| 2 | 3.065 | | 3.366 | | 3.447 | | 3.466 | | 3.622 | | 3.665 |
| 3 | 3.072 | | 3.380 | | 3.462 | | 3.482 | | 3.638 | | 3.682 |
| 均值 | 3.061 | | 3.361 | | 3.443 | | 3.463 | | 3.620 | | 3.665 |
| COV | 0.35% | | 0.52% | | 0.49% | | 0.49% | | 0.43% | | 0.39% |
| V-2 | 样品5 | 1 | 3.047 | | 3.434 | | 3.565 | | 3.599 | | 3.906 | | 4.014 |
| 2 | 3.065 | | 3.464 | | 3.592 | | 3.626 | | 3.932 | | 4.035 |
| 3 | 3.072 | | 3.478 | | 3.609 | | 3.644 | | 3.951 | | 4.057 |
| 均值 | 3.061 | | 3.458 | | 3.589 | | 3.623 | | 3.930 | | 4.035 |
| COV | 0.35% | | 0.54% | | 0.51% | | 0.51% | | 0.46% | | 0.43% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| F | 样品6 | 1 | 3.006 | | 3.266 | | 3.308 | | 3.464 | | 3.763 | | 3.842 |
| 2 | 2.995 | | 3.280 | | 3.275 | | 3.466 | | 3.746 | | 3.851 |
| 3 | 3.004 | | 3.270 | | 3.293 | | 3.462 | | 3.743 | | 3.840 |
| 均值 | 3.002 | | 3.272 | | 3.292 | | 3.464 | | 3.751 | | 3.844 |
| COV | 0.16% | | 0.19% | | 0.41% | | 0.06% | | 0.24% | | 0.12% |
| Q | 样品6 | 1 | 3.086 | | 3.290 | | 3.380 | | 3.433 | | 3.614 | | 3.656 |
| 2 | 3.077 | | 3.316 | | 3.383 | | 3.408 | | 3.621 | | 3.676 |
| 3 | 3.055 | | 3.312 | | 3.372 | | 3.421 | | 3.603 | | 3.661 |
| 均值 | 3.073 | | 3.306 | | 3.378 | | 3.421 | | 3.613 | | 3.664 |
| COV | 0.42% | | 0.35% | | 0.14% | | 0.30% | | 0.21% | | 0.23% |
| D | 样品6 | 1 | 2.988 | | 3.231 | | 3.314 | | 3.337 | | 3.535 | | 3.600 |
| 2 | 2.997 | | 3.243 | | 3.328 | | 3.350 | | 3.548 | | 3.612 |
| 3 | 2.985 | | 3.233 | | 3.319 | | 3.343 | | 3.540 | | 3.608 |
| 均值 | 2.990 | | 3.235 | | 3.320 | | 3.343 | | 3.541 | | 3.607 |
| COV | 0.18% | | 0.17% | | 0.17% | | 0.16% | | 0.16% | | 0.14% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| F | 样品7 | 1 | 3.005 | | 3.274 | | 3.385 | | 3.401 | | 3.748 | | 3.850 |
| 2 | 2.997 | | 3.266 | | 3.380 | | 3.417 | | 3.753 | | 3.864 |
| 3 | 3.003 | | 3.287 | | 3.373 | | 3.391 | | 3.752 | | 3.863 |
| 均值 | 3.002 | | 3.275 | | 3.379 | | 3.403 | | 3.751 | | 3.859 |
| COV | 0.13% | | 0.26% | | 0.14% | | 0.31% | | 0.07% | | 0.17% |
| B | 样品7 | 1 | 3.186 | | 3.421 | | 3.673 | | 3.885 | | 3.991 | | 4.131 |
| 2 | 3.122 | | 3.486 | | 3.686 | | 3.899 | | 4.002 | | 4.215 |
| 3 | 3.136 | | 3.478 | | 3.728 | | 3.854 | | 3.948 | | 4.226 |
| 均值 | 3.148 | | 3.462 | | 3.696 | | 3.879 | | 3.980 | | 4.191 |
| COV | 0.88% | | 0.84% | | 0.64% | | 0.49% | | 0.59% | | 1.01% |
| P | 样品7 | 1 | 3.066 | | 3.301 | | 3.409 | | 3.465 | | 3.656 | | 3.751 |
| 2 | 3.066 | | 3.313 | | 3.430 | | 3.486 | | 3.681 | | 3.778 |
| 3 | 3.071 | | 3.315 | | 3.427 | | 3.484 | | 3.675 | | 3.769 |
| 均值 | 3.068 | | 3.310 | | 3.422 | | 3.478 | | 3.671 | | 3.766 |
| COV | 0.08% | | 0.18% | | 0.27% | | 0.26% | | 0.29% | | 0.31% |
| D | 样品7 | 1 | 3.000 | | 3.249 | | 3.344 | | 3.370 | | 3.598 | | 3.676 |
| 2 | 3.004 | | 3.253 | | 3.348 | | 3.373 | | 3.603 | | 3.681 |
| 3 | 3.000 | | 3.254 | | 3.350 | | 3.377 | | 3.607 | | 3.684 |
| 均值 | 3.001 | | 3.252 | | 3.347 | | 3.373 | | 3.603 | | 3.680 |
| COV | 0.06% | | 0.06% | | 0.08% | | 0.09% | | 0.10% | | 0.09% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| P-1 | 样品8 | 1 | 3.188 | | 3.488 | | 3.410 | | 3.659 | | 3.855 | | 3.949 |
| 2 | 3.200 | | 3.508 | | 3.633 | | 3.688 | | 3.894 | | 3.987 |
| 3 | 3.204 | | 3.516 | | 3.635 | | 3.692 | | 3.893 | | 3.994 |
| 均值 | 3.197 | | 3.504 | | 3.560 | | 3.680 | | 3.881 | | 3.977 |
| COV | 0.21% | | 0.34% | | 2.97% | | 0.39% | | 0.47% | | 0.49% |
| P-2 | 样品8 | 1 | 3.306 | | 3.508 | | 3.620 | | 3.676 | | 3.873 | | 3.962 |
| 2 | 3.194 | | 3.493 | | 3.617 | | 3.668 | | 3.873 | | 3.961 |
| 3 | 3.193 | | 3.497 | | 3.614 | | 3.671 | | 3.869 | | 3.957 |
| 均值 | 3.231 | | 3.499 | | 3.617 | | 3.672 | | 3.872 | | 3.960 |
| COV | 1.63% | | 0.17% | | 0.07% | | 0.10% | | 0.05% | | 0.06% |
| G | 样品8 | 1 | 3.150 | | 3.473 | | 3.592 | | 3.625 | | 3.882 | | 3.975 |
| 2 | 3.154 | | 3.477 | | 3.585 | | 3.618 | | 3.874 | | 3.966 |
| 3 | 3.170 | | 3.508 | | 3.630 | | 3.665 | | 3.928 | | 4.010 |
| 均值 | 3.158 | | 3.486 | | 3.602 | | 3.636 | | 3.895 | | 3.984 |
| COV | 0.27% | | 0.45% | | 0.55% | | 0.57% | | 0.60% | | 0.47% |
| F | 样品8 | 1 | 3.118 | | 3.516 | | 3.660 | | 3.713 | | 4.025 | | 4.143 |
| 2 | 3.108 | | 3.495 | | 3.651 | | 3.682 | | 4.024 | | 4.150 |
| 3 | 3.138 | | 3.517 | | 3.644 | | 3.712 | | 4.038 | | 4.145 |
| 均值 | 3.121 | | 3.509 | | 3.652 | | 3.702 | | 4.029 | | 4.146 |
| COV | 0.39% | | 0.29% | | 0.18% | | 0.39% | | 0.16% | | 0.08% |
| B | 样品8 | 1 | 3.186 | | 3.421 | | 3.673 | | 3.885 | | 3.991 | | 4.131 |
| 2 | 3.122 | | 3.486 | | 3.686 | | 3.899 | | 4.002 | | 4.215 |
| 3 | 3.136 | | 3.478 | | 3.728 | | 3.854 | | 3.948 | | 4.226 |
| 均值 | 3.148 | | 3.462 | | 3.696 | | 3.879 | | 3.980 | | 4.191 |
| COV | 0.88% | | 0.84% | | 0.64% | | 0.49% | | 0.59% | | 1.01% |
| T | 样品8 | 1 | 3.090 | | 3.383 | | 3.484 | | 3.507 | | 3.719 | | 3.783 |
| 2 | 3.093 | | 3.389 | | 3.487 | | 3.516 | | 3.721 | | 3.779 |
| 3 | 3.084 | | 3.401 | | 3.505 | | 3.528 | | 3.735 | | 3.799 |
| 均值 | 3.089 | | 3.391 | | 3.492 | | 3.517 | | 3.725 | | 3.787 |
| COV | 0.12% | | 0.22% | | 0.27% | | 0.24% | | 0.20% | | 0.23% |
| N | 样品8 | 1 | 3.152 | | 3.495 | | 3.605 | | 3.630 | | 3.841 | | 3.900 |
| 2 | 3.166 | | 3.510 | | 3.618 | | 3.646 | | 3.852 | | 3.911 |
| 3 | 3.153 | | 3.496 | | 3.602 | | 3.631 | | 3.835 | | 3.897 |
| 均值 | 3.157 | | 3.501 | | 3.609 | | 3.635 | | 3.843 | | 3.902 |
| COV | 0.20% | | 0.20% | | 0.20% | | 0.20% | | 0.18% | | 0.16% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| Q | 样品10 | 1 | 3.760 | | 4.111 | | 4.218 | | 4.239 | | 4.508 | | 4.584 |
| 2 | 3.766 | | 4.109 | | 4.230 | | 4.258 | | 4.480 | | 4.569 |
| 3 | 3.743 | | 4.100 | | 4.224 | | 4.250 | | 4.497 | | 4.567 |
| 均值 | 3.756 | | 4.107 | | 4.224 | | 4.249 | | 4.495 | | 4.573 |
| COV | 0.26% | | 0.12% | | 0.12% | | 0.18% | | 0.26% | | 0.17% |
| H-1 | 样品10 | 1 | 3.690 | | 4.140 | | 4.300 | | 4.340 | | 4.730 | | 4.870 |
| 2 | 3.710 | | 4.150 | | 4.310 | | 4.350 | | 4.740 | | 4.890 |
| 3 | 3.710 | | 4.150 | | 4.310 | | 4.350 | | 4.730 | | 4.880 |
| 均值 | 3.703 | | 4.147 | | 4.307 | | 4.347 | | 4.733 | | 4.880 |
| COV | 0.25% | | 0.11% | | 0.11% | | 0.11% | | 0.10% | | 0.17% |
| H-2 | 样品10 | 1 | 3.710 | | 4.150 | | 4.310 | | 4.360 | | 4.740 | | 4.880 |
| 2 | 3.700 | | 4.150 | | 4.300 | | 4.350 | | 4.740 | | 4.880 |
| 3 | 3.720 | | 4.170 | | 4.330 | | 4.380 | | 4.780 | | 4.920 |
| 均值 | 3.710 | | 4.157 | | 4.313 | | 4.363 | | 4.753 | | 4.893 |
| COV | 0.22% | | 0.23% | | 0.29% | | 0.29% | | 0.40% | | 0.39% |
| H-3 | 样品10 | 1 | 3.700 | | 4.140 | | 4.300 | | 4.350 | | 4.730 | | 4.880 |
| 2 | 3.710 | | 4.150 | | 4.300 | | 4.350 | | 4.730 | | 4.880 |
| 3 | 3.710 | | 4.160 | | 4.320 | | 4.360 | | 4.750 | | 4.890 |
| 均值 | 3.707 | | 4.150 | | 4.307 | | 4.353 | | 4.737 | | 4.883 |
| COV | 0.13% | | 0.20% | | 0.22% | | 0.11% | | 0.20% | | 0.10% |
| E | 样品10 | 1 | 3.680 | | 4.080 | | 4.220 | | 4.250 | | 4.530 | | 4.620 |
| 2 | 3.700 | | 4.090 | | 4.210 | | 4.260 | | 4.520 | | 4.610 |
| 3 | 3.700 | | 4.080 | | 4.220 | | 4.300 | | 4.550 | | 4.640 |
| 均值 | 3.693 | | 4.083 | | 4.217 | | 4.270 | | 4.533 | | 4.623 |
| COV | 0.26% | | 0.12% | | 0.11% | | 0.51% | | 0.28% | | 0.27% |
| C | 样品10 | 1 | 3.670 | | 4.000 | | 4.100 | | 4.130 | | / | | / |
| 2 | 3.680 | | 4.010 | | 4.110 | | 4.140 | | / | | / |
| 3 | 3.680 | | 4.010 | | 4.120 | | 4.140 | | / | | / |
| 均值 | 3.677 | | 4.007 | | 4.110 | | 4.137 | | / | | / |
| COV | 0.13% | | 0.12% | | 0.20% | | 0.11% | | / | | / |
| N | 样品10 | 1 | 3.630 | | 3.955 | | 4.060 | | 4.088 | | 4.302 | | 4.369 |
| 2 | 3.642 | | 3.972 | | 4.078 | | 4.106 | | 4.323 | | 4.388 |
| 3 | 3.629 | | 3.962 | | 4.069 | | 4.098 | | 4.315 | | 4.383 |
| 均值 | 3.634 | | 3.963 | | 4.069 | | 4.097 | | 4.313 | | 4.380 |
| COV | 0.16% | | 0.17% | | 0.18% | | 0.18% | | 0.20% | | 0.18% |
| V-1 | 样品10 | 1 | 3.586 | | 3.855 | | 3.936 | | 3.957 | | 4.111 | | 4.155 |
| 2 | 3.590 | | 3.863 | | 3.945 | | 3.970 | | 4.123 | | 4.168 |
| 3 | 3.588 | | 3.863 | | 3.944 | | 3.965 | | 4.122 | | 4.167 |
| 均值 | 3.588 | | 3.860 | | 3.942 | | 3.964 | | 4.119 | | 4.163 |
| COV | 0.05% | | 0.10% | | 0.10% | | 0.13% | | 0.13% | | 0.15% |
| V-2 | 样品10 | 1 | 3.586 | | 3.984 | | 4.127 | | 4.168 | | 4.515 | | 4.637 |
| 2 | 3.590 | | 3.993 | | 4.137 | | 4.182 | | 4.530 | | 4.655 |
| 3 | 3.588 | | 3.992 | | 4.136 | | 4.176 | | 4.529 | | 4.654 |
| 均值 | 3.588 | | 3.989 | | 4.133 | | 4.176 | | 4.524 | | 4.649 |
| COV | 0.05% | | 0.10% | | 0.11% | | 0.14% | | 0.15% | | 0.17% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| F | 样品11 | 1 | 3.758 | | 4.148 | | 4.293 | | 4.346 | | 4.712 | | 4.833 |
| 2 | 3.745 | | 4.154 | | 4.296 | | 4.350 | | 4.709 | | 4.834 |
| 3 | 3.744 | | 4.155 | | 4.284 | | 4.341 | | 4.723 | | 4.833 |
| 均值 | 3.749 | | 4.152 | | 4.291 | | 4.345 | | 4.715 | | 4.833 |
| COV | 0.17% | | 0.07% | | 0.12% | | 0.08% | | 0.13% | | 0.01% |
| B | 样品11 | 1 | 3.542 | | 3.965 | | 4.215 | | 4.445 | | 4.576 | | 4.854 |
| 2 | 3.600 | | 3.916 | | 4.230 | | 4.403 | | 4.526 | | 4.800 |
| 3 | 3.575 | | 3.918 | | 4.167 | | 4.455 | | 4.616 | | 4.867 |
| 均值 | 3.572 | | 3.933 | | 4.204 | | 4.434 | | 4.573 | | 4.840 |
| COV | 0.67% | | 0.58% | | 0.64% | | 0.51% | | 0.81% | | 0.60% |
| Q | 样品11 | 1 | 3.850 | | 4.145 | | 4.265 | | 4.269 | | 4.517 | | 4.564 |
| 2 | 3.846 | | 4.162 | | 4.238 | | 4.274 | | 4.540 | | 4.596 |
| 3 | 3.845 | | 4.147 | | 4.247 | | 4.285 | | 4.521 | | 4.570 |
| 均值 | 3.847 | | 4.151 | | 4.250 | | 4.276 | | 4.526 | | 4.577 |
| COV | 0.06% | | 0.18% | | 0.26% | | 0.16% | | 0.22% | | 0.30% |
| `N | 样品11 | 1 | 3.700 | | 3.995 | | 4.092 | | 4.115 | | 4.322 | | 4.386 |
| 2 | 3.700 | | 3.995 | | 4.090 | | 4.114 | | 4.315 | | 4.378 |
| 3 | 3.705 | | 4.002 | | 4.098 | | 4.122 | | 4.325 | | 4.389 |
| 均值 | 3.702 | | 3.998 | | 4.093 | | 4.117 | | 4.321 | | 4.384 |
| COV | 0.07% | | 0.08% | | 0.08% | | 0.09% | | 0.10% | | 0.10% |
| D | 样品11 | 1 | 3.734 | | 4.043 | | 4.144 | | 4.172 | | 4.398 | | 4.471 |
| 2 | 3.735 | | 4.041 | | 4.142 | | 4.170 | | 4.396 | | 4.470 |
| 3 | 3.735 | | 4.045 | | 4.146 | | 4.174 | | 4.402 | | 4.477 |
| 均值 | 3.734 | | 4.043 | | 4.144 | | 4.172 | | 4.398 | | 4.473 |
| COV | 0.01% | | 0.04% | | 0.05% | | 0.05% | | 0.06% | | 0.07% |

实验二：卸压测试条件下样品测试（自动）

如表8所示是不同实验室针对不同样品进行的压实密度测试的原始数据。同一实验室内，在各个压强下，三次测试结果的重复性较好。除个别实验室外，变异系数（COV）在1%以内。

表8 实验二条件下各实验室的压实密度原始数据（g/cm3）

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| A | 样品1 | 1 | 2.262 | 2.388 | | 2.456 | | 2.515 | | 2.551 | | 2.585 | |
| 2 | 2.266 | 2.388 | | 2.462 | | 2.522 | | 2.551 | | 2.587 | |
| 3 | 2.262 | 2.392 | | 2.460 | | 2.519 | | 2.554 | | 2.592 | |
| 均值 | 2.263 | 2.389 | | 2.459 | | 5.519 | | 2.552 | | 2.588 | |
| COV | 0.19% | 0.19% | | 0.25% | | 0.29% | | 0.14% | | 0.29% | |
| G | 样品1 | 1 | 1.968 | 2.065 | | 2.113 | | 2.163 | | 2.183 | | 2.204 | |
| 2 | 1.967 | 2.063 | | 2.120 | | 2.169 | | 2.189 | | 2.210 | |
| 3 | 1.974 | 2.062 | | 2.119 | | 2.168 | | 2.188 | | 2.209 | |
| 均值 | 1.970 | 2.063 | | 2.117 | | 2.167 | | 2.186 | | 2.208 | |
| COV | 0.17% | 0.06% | | 0.13% | | 0.12% | | 0.12% | | 0.12% | |
| H-1 | 样品1 | 1 | 1.940 | 2.030 | | 2.090 | | 2.130 | | 2.160 | | 2.180 | |
| 2 | 1.940 | 2.030 | | 2.080 | | 2.130 | | 2.150 | | 2.180 | |
| 3 | 1.950 | 2.040 | | 2.090 | | 2.140 | | 2.160 | | 2.190 | |
| 均值 | 1.943 | 2.033 | | 2.087 | | 2.133 | | 2.157 | | 2.183 | |
| COV | 0.24% | 0.23% | | 0.23% | | 0.22% | | 0.22% | | 0.22% | |
| H-2 | 样品1 | 1 | 1.940 | 2.040 | | 2.090 | | 2.140 | | 2.170 | | 2.190 | |
| 2 | 1.960 | 2.050 | | 2.100 | | 2.150 | | 2.180 | | 2.200 | |
| 3 | 1.960 | 2.050 | | 2.100 | | 2.150 | | 2.180 | | 2.200 | |
| 均值 | 1.953 | 2.047 | | 2.097 | | 2.147 | | 2.177 | | 2.197 | |
| COV | 0.48% | 0.23% | | 0.22% | | 0.22% | | 0.22% | | 0.21% | |
| E | 样品1 | 1 | 1.980 | 2.080 | | 2.120 | | 2.180 | | 2.200 | | 2.230 | |
| 2 | 1.990 | 2.090 | | 2.140 | | 2.190 | | 2.210 | | 2.240 | |
| 3 | 1.990 | 2.080 | | 2.140 | | 2.180 | | 2.210 | | 2.230 | |
| 均值 | 1.987 | 2.083 | | 2.133 | | 2.183 | | 2.207 | | 2.233 | |
| COV | 0.24% | 0.23% | | 0.44% | | 0.22% | | 0.21% | | 0.21% | |
| C | 样品1 | 1 | 2.000 | 2.100 | | 2.160 | | 2.210 | | 2.240 | | / | |
| 2 | 2.000 | 2.110 | | 2.170 | | 2.220 | | 2.240 | | / | |
| 3 | 2.000 | 2.110 | | 2.170 | | 2.220 | | 2.240 | | / | |
| 均值 | 2.000 | 2.107 | | 2.167 | | 2.217 | | 2.240 | | / | |
| COV | 0.00% | 0.22% | | 0.22% | | 0.21% | | 0.00% | | / | |
| T | 样品1 | 1 | 1.973 | 2.118 | | 2.185 | | 2.248 | | 2.263 | | 2.304 | |
| 2 | 1.991 | 2.128 | | 2.196 | | 2.259 | | 2.272 | | 2.312 | |
| 3 | 1.981 | 2.128 | | 2.197 | | 2.262 | | 2.276 | | 2.314 | |
| 均值 | 1.982 | 2.125 | | 2.193 | | 2.257 | | 2.270 | | 2.310 | |
| COV | 0.37% | 0.23% | | 0.25% | | 0.26% | | 0.24% | | 0.19% | |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| A | 样品3 | 1 | 2.387 | 2.523 | | 2.601 | | 2.665 | | 2.698 | | 2.733 | |
| 2 | 2.402 | 2.526 | | 2.607 | | 2.688 | | 2.709 | | 2.747 | |
| 3 | 2.389 | 2.521 | | 2.598 | | 2.661 | | 2.693 | | 2.731 | |
| 均值 | 2.393 | 2.523 | | 2.602 | | 2.671 | | 2.7 | | 2.737 | |
| COV | 0.66% | 0.21% | | 0.37% | | 1.19% | | 0.67% | | 0.71% | |
| G | 样品3 | 1 | 2.079 | 2.178 | | 2.241 | | 2.285 | | 2.308 | | 2.331 | |
| 2 | 2.080 | 2.178 | | 2.241 | | 2.285 | | 2.308 | | 2.331 | |
| 3 | 2.087 | 2.185 | | 2.238 | | 2.294 | | 2.305 | | 2.340 | |
| 均值 | 2.082 | 2.180 | | 2.240 | | 2.288 | | 2.307 | | 2.334 | |
| COV | 0.16% | 0.14% | | 0.06% | | 0.18% | | 0.06% | | 0.18% | |
| H-1 | 样品3 | 1 | 2.070 | 2.170 | | 2.230 | | 2.280 | | 2.300 | | 2.330 | |
| 2 | 2.070 | 2.170 | | 2.230 | | 2.280 | | 2.300 | | 2.330 | |
| 3 | 2.060 | 2.160 | | 2.220 | | 2.270 | | 2.290 | | 2.320 | |
| 均值 | 2.067 | 2.167 | | 2.227 | | 2.277 | | 2.297 | | 2.327 | |
| COV | 0.23% | 0.22% | | 0.21% | | 0.21% | | 0.21% | | 0.20% | |
| H-2 | 样品3 | 1 | 2.060 | 2.170 | | 2.220 | | 2.270 | | 2.300 | | 2.330 | |
| 2 | 2.050 | 2.160 | | 2.220 | | 2.260 | | 2.290 | | 2.320 | |
| 3 | 2.080 | 2.180 | | 2.230 | | 2.290 | | 2.310 | | 2.340 | |
| 均值 | 2.063 | 2.170 | | 2.223 | | 2.273 | | 2.300 | | 2.330 | |
| COV | 0.60% | 0.38% | | 0.21% | | 0.55% | | 0.35% | | 0.35% | |
| E | 样品3 | 1 | 2.090 | 2.180 | | 2.240 | | 2.280 | | 2.310 | | 2.340 | |
| 2 | 2.070 | 2.160 | | 2.230 | | 2.270 | | 2.300 | | 2.320 | |
| 3 | 2.080 | 2.190 | | 2.240 | | 2.290 | | 2.310 | | 2.340 | |
| 均值 | 2.080 | 2.177 | | 2.237 | | 2.280 | | 2.307 | | 2.333 | |
| COV | 0.39% | 0.57% | | 0.21% | | 0.36% | | 0.20% | | 0.40% | |
| T | 样品3 | 1 | 2.061 | 2.182 | | 2.245 | | 2.304 | | 2.317 | | 2.355 | |
| 2 | 2.056 | 2.176 | | 2.233 | | 2.297 | | 2.311 | | 2.347 | |
| 3 | 2.058 | 2.177 | | 2.240 | | 2.300 | | 2.314 | | 2.351 | |
| 均值 | 2.058 | 2.178 | | 2.239 | | 2.300 | | 2.314 | | 2.351 | |
| COV | 0.11% | 0.13% | | 0.22% | | 0.12% | | 0.12% | | 0.15% | |
| C | 样品3 | 1 | 2.080 | 2.190 | | 2.250 | | 2.300 | | 2.320 | | / | |
| 2 | 2.080 | 2.190 | | 2.250 | | 2.300 | | 2.320 | | / | |
| 3 | 2.090 | 2.190 | | 2.250 | | 2.300 | | 2.320 | | / | |
| 均值 | 2.083 | 2.190 | | 2.250 | | 2.300 | | 2.320 | | / | |
| COV | 0.23% | 0.00% | | 0.00% | | 0.00% | | 0.00% | | / | |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| R | 样品4 | 1 | 1.953 | 2.046 | | 2.141 | | 2.227 | | 2.237 | | 2.312 | |
| 2 | 1.934 | 2.032 | | 2.139 | | 2.220 | | 2.268 | | 2.257 | |
| 3 | 1.948 | 2.017 | | 2.142 | | 2.235 | | 2.273 | | 2.291 | |
| 均值 | 1.945 | 2.032 | | 2.141 | | 2.227 | | 2.260 | | 2.286 | |
| COV | 0.42% | 0.59% | | 0.07% | | 0.27% | | 0.70% | | 0.99% | |
| P | 样品4 | 1 | 2.041 | 2.135 | | 2.188 | | 2.259 | | 2.268 | | 2.296 | |
| 2 | 2.043 | 2.137 | | 2.194 | | 2.262 | | 2.272 | | 2.305 | |
| 3 | 2.036 | 2.130 | | 2.186 | | 2.255 | | 2.265 | | 2.294 | |
| 均值 | 2.040 | 2.134 | | 2.190 | | 2.259 | | 2.269 | | 2.298 | |
| COV | 0.15% | 0.15% | | 0.15% | | 0.13% | | 0.13% | | 0.21% | |
| T | 样品4 | 1 | 2.035 | 2.155 | | 2.217 | | 2.277 | | 2.290 | | 2.328 | |
| 2 | 2.039 | 2.158 | | 2.219 | | 2.277 | | 2.291 | | 2.327 | |
| 3 | 2.040 | 2.159 | | 2.220 | | 2.280 | | 2.294 | | 2.331 | |
| 均值 | 2.038 | 2.157 | | 2.219 | | 2.278 | | 2.291 | | 2.329 | |
| COV | 0.10% | 0.07% | | 0.05% | | 0.06% | | 0.07% | | 0.08% | |
| N | 样品4 | 1 | 2.055 | 2.159 | | 2.220 | | 2.272 | | 2.295 | | 2.323 | |
| 2 | 2.055 | 2.159 | | 2.221 | | 2.272 | | 2.296 | | 2.325 | |
| 3 | 2.059 | 2.164 | | 2.225 | | 2.277 | | 2.301 | | 2.330 | |
| 均值 | 2.056 | 2.161 | | 2.222 | | 2.274 | | 2.297 | | 2.326 | |
| COV | 0.08% | 0.09% | | 0.09% | | 0.11% | | 0.10% | | 0.13% | |
| D | 样品4 | 1 | 2.065 | 2.171 | | 2.236 | | 2.290 | | 2.311 | | 2.341 | |
| 2 | 2.069 | 2.171 | | 2.236 | | 2.288 | | 2.312 | | 2.340 | |
| 3 | 2.066 | 2.169 | | 2.228 | | 2.278 | | 2.300 | | 2.328 | |
| 均值 | 2.067 | 2.170 | | 2.233 | | 2.285 | | 2.308 | | 2.336 | |
| COV | 0.08% | 0.04% | | 0.16% | | 0.24% | | 0.25% | | 0.26% | |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| A | 样品5 | 1 | 3.041 | | 3.321 | | 3.420 | | 3.459 | | 3.605 | | 3.666 |
| 2 | 3.054 | | 3.347 | | 3.447 | | 3.488 | | 3.633 | | 3.693 |
| 3 | 3.050 | | 3.336 | | 3.436 | | 3.476 | | 3.620 | | 3.681 |
| 均值 | 3.048 | | 3.335 | | 3.434 | | 3.474 | | 3.619 | | 3.680 |
| COV | 0.18% | | 0.32% | | 0.32% | | 0.34% | | 0.32% | | 0.30% |
| G | 样品5 | 1 | 3.044 | | 3.306 | | 3.393 | | 3.443 | | 3.583 | | 3.627 |
| 2 | 3.040 | | 3.311 | | 3.399 | | 3.439 | | 3.578 | | 3.635 |
| 3 | 3.044 | | 3.316 | | 3.405 | | 3.445 | | 3.585 | | 3.642 |
| 均值 | 3.043 | | 3.311 | | 3.399 | | 3.442 | | 3.582 | | 3.634 |
| COV | 0.06% | | 0.13% | | 0.14% | | 0.07% | | 0.08% | | 0.16% |
| H-1 | 样品5 | 1 | 3.000 | | 3.270 | | 3.360 | | 3.400 | | 3.550 | | 3.620 |
| 2 | 3.000 | | 3.280 | | 3.370 | | 3.410 | | 3.570 | | 3.630 |
| 3 | 3.050 | | 3.320 | | 3.420 | | 3.460 | | 3.600 | | 3.660 |
| 均值 | 3.017 | | 3.290 | | 3.383 | | 3.423 | | 3.573 | | 3.637 |
| COV | 0.78% | | 0.66% | | 0.78% | | 0.77% | | 0.58% | | 0.47% |
| H-2 | 样品5 | 1 | 3.000 | | 3.280 | | 3.370 | | 3.410 | | 3.560 | | 3.620 |
| 2 | 3.010 | | 3.280 | | 3.380 | | 3.420 | | 3.570 | | 3.630 |
| 3 | 3.050 | | 3.350 | | 3.450 | | 3.500 | | 3.650 | | 3.700 |
| 均值 | 3.020 | | 3.303 | | 3.400 | | 3.443 | | 3.593 | | 3.650 |
| COV | 0.72% | | 1.00% | | 1.05% | | 1.17% | | 1.12% | | 0.98% |
| H-3 | 样品5 | 1 | 2.970 | | 3.240 | | 3.330 | | 3.370 | | 3.520 | | 3.580 |
| 2 | 3.030 | | 3.330 | | 3.430 | | 3.480 | | 3.630 | | 3.680 |
| 3 | 2.970 | | 3.240 | | 3.330 | | 3.370 | | 3.530 | | 3.590 |
| 均值 | 2.990 | | 3.270 | | 3.363 | | 3.407 | | 3.560 | | 3.617 |
| COV | 0.95% | | 1.30% | | 1.40% | | 1.52% | | 1.40% | | 1.24% |
| H-4 | 样品5 | 1 | 2.970 | | 3.250 | | 3.340 | | 3.380 | | 3.530 | | 3.590 |
| 2 | 2.960 | | 3.240 | | 3.340 | | 3.370 | | 3.520 | | 3.580 |
| 3 | 2.970 | | 3.240 | | 3.330 | | 3.370 | | 3.520 | | 3.580 |
| 均值 | 2.967 | | 3.243 | | 3.337 | | 3.373 | | 3.523 | | 3.583 |
| COV | 0.16% | | 0.15% | | 0.14% | | 0.14% | | 0.13% | | 0.13% |
| E | 样品5 | 1 | 3.000 | | 3.270 | | 3.360 | | 3.410 | | 3.530 | | 3.569 |
| 2 | 3.000 | | 3.280 | | 3.370 | | 3.410 | | 3.540 | | 3.610 |
| 3 | 3.010 | | 3.280 | | 3.370 | | 3.420 | | 3.540 | | 3.600 |
| 均值 | 3.003 | | 3.277 | | 3.367 | | 3.413 | | 3.537 | | 3.593 |
| COV | 0.16% | | 0.14% | | 0.14% | | 0.14% | | 0.13% | | 0.49% |
| Q | 样品5 | 1 | 3.067 | | 3.350 | | 3.408 | | 3.409 | | 3.567 | | 3.614 |
| 2 | 3.056 | | 3.377 | | 3.399 | | 3.424 | | 3.568 | | 3.616 |
| 3 | 3.062 | | 3.341 | | 3.398 | | 3.420 | | 3.572 | | 3.621 |
| 均值 | 3.062 | | 3.356 | | 3.402 | | 3.418 | | 3.569 | | 3.617 |
| COV | 0.15% | | 0.46% | | 0.13% | | 0.19% | | 0.06% | | 0.08% |
| C | 样品5 | 1 | 3.100 | | 3.410 | | 3.510 | | 3.550 | | / | | / |
| 2 | 3.070 | | 3.380 | | 3.480 | | 3.520 | | / | | / |
| 3 | 3.060 | | 3.370 | | 3.470 | | 3.510 | | / | | / |
| 均值 | 3.077 | | 3.387 | | 3.487 | | 3.527 | | / | | / |
| COV | 0.55% | | 0.50% | | 0.49% | | 0.48% | | / | | / |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| F | 样品6 | 1 | 2.910 | | 3.053 | | 3.077 | | 3.165 | | 3.301 | | 3.307 |
| 2 | 2.890 | | 3.063 | | 3.054 | | 3.170 | | 3.279 | | 3.341 |
| 3 | 2.910 | | 3.048 | | 3.070 | | 3.148 | | 3.289 | | 3.325 |
| 均值 | 2.903 | | 3.054 | | 3.067 | | 3.161 | | 3.290 | | 3.324 |
| COV | 0.32% | | 0.21% | | 0.32% | | 0.30% | | 0.28% | | 0.42% |
| B | 样品6 | 1 | 2.938 | | 3.141 | | 3.203 | | 3.226 | | 3.361 | | 3.397 |
| 2 | 2.942 | | 3.143 | | 3.207 | | 3.225 | | / | | / |
| 3 | 2.941 | | 3.141 | | 3.205 | | 3.228 | | / | | / |
| 均值 | 2.941 | | 3.141 | | 3.205 | | 3.226 | | 3.361 | | 3.397 |
| COV | 0.05% | | 0.03% | | 0.05% | | 0.03% | | / | | / |
| Q | 样品6 | 1 | 3.018 | | 3.146 | | 3.213 | | 3.244 | | 3.374 | | 3.376 |
| 2 | 3.002 | | 3.166 | | 3.214 | | 3.221 | | 3.360 | | 3.405 |
| 3 | 2.980 | | 3.162 | | 3.200 | | 3.236 | | 3.343 | | 3.389 |
| 均值 | 3.000 | | 3.158 | | 3.209 | | 3.234 | | 3.359 | | 3.390 |
| COV | 0.52% | | 0.27% | | 0.20% | | 0.29% | | 0.38% | | 0.35% |
| D | 样品6 | 1 | 2.949 | | 3.150 | | 3.230 | | 3.273 | | 3.395 | | 3.462 |
| 2 | 2.942 | | 3.146 | | 3.228 | | 3.270 | | 3.394 | | 3.462 |
| 3 | 2.947 | | 3.153 | | 3.234 | | 3.278 | | 3.402 | | 3.472 |
| 均值 | 2.946 | | 3.149 | | 3.231 | | 3.274 | | 3.397 | | 3.465 |
| COV | 0.10% | | 0.10% | | 0.09% | | 0.10% | | 0.11% | | 0.14% |
| R | 样品6 | 1 | 2.795 | | 3.069 | | 3.150 | | 3.214 | | 3.283 | | 3.364 |
| 2 | 2.822 | | 3.015 | | 3.161 | | 3.224 | | 3.298 | | 3.386 |
| 3 | 2.782 | | 3.046 | | 3.182 | | 3.233 | | 3.299 | | 3.373 |
| 均值 | 2.800 | | 3.043 | | 3.164 | | 3.224 | | 3.293 | | 3.375 |
| COV | 0.60% | | 0.73% | | 0.42% | | 0.23% | | 0.22% | | 0.27% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| F | 样品7 | 1 | 2.908 | | 3.043 | | 3.093 | | 3.094 | | 3.282 | | 3.320 |
| 2 | 2.879 | | 3.035 | | 3.095 | | 3.115 | | 3.282 | | 3.329 |
| 3 | 2.907 | | 3.063 | | 3.089 | | 3.094 | | 3.295 | | 3.325 |
| 均值 | 2.898 | | 3.047 | | 3.092 | | 3.101 | | 3.287 | | 3.325 |
| COV | 0.45% | | 0.38% | | 0.09% | | 0.33% | | 0.18% | | 0.10% |
| B | 样品7 | 1 | 2.964 | | 3.067 | | 3.145 | | 3.222 | | 3.222 | | 3.305 |
| 2 | 2.848 | | 2.999 | | 3.160 | | 3.238 | | 3.187 | | 3.286 |
| 3 | 2.916 | | 3.022 | | 3.149 | | 3.161 | | 3.259 | | 3.283 |
| 均值 | 2.909 | | 3.030 | | 3.151 | | 3.207 | | 3.223 | | 3.291 |
| COV | 1.64% | | 0.94% | | 0.20% | | 1.03% | | 0.92% | | 0.30% |
| P | 样品7 | 1 | 2.961 | | 3.137 | | 3.216 | | 3.270 | | 3.375 | | 3.458 |
| 2 | 2.964 | | 3.143 | | 3.219 | | 3.282 | | 3.384 | | 3.463 |
| 3 | 2.965 | | 3.146 | | 3.221 | | 3.279 | | 3.386 | | 3.464 |
| 均值 | 2.964 | | 3.142 | | 3.219 | | 3.277 | | 3.382 | | 3.462 |
| COV | 0.06% | | 0.12% | | 0.06% | | 0.16% | | 0.14% | | 0.08% |
| D | 样品7 | 1 | 2.968 | | 3.169 | | 3.258 | | 3.306 | | 3.445 | | 3.521 |
| 2 | 2.972 | | 3.175 | | 3.265 | | 3.313 | | 3.454 | | 3.530 |
| 3 | 2.961 | | 3.164 | | 3.254 | | 3.302 | | 3.442 | | 3.520 |
| 均值 | 2.967 | | 3.169 | | 3.259 | | 3.307 | | 3.447 | | 3.524 |
| COV | 0.16% | | 0.14% | | 0.14% | | 0.14% | | 0.15% | | 0.12% |
| R | 样品7 | 1 | 2.799 | | 3.085 | | 3.127 | | 3.168 | | 3.247 | | 3.430 |
| 2 | 2.808 | | 3.053 | | 3.135 | | 3.171 | | 3.306 | | 3.434 |
| 3 | 2.844 | | 3.061 | | 3.125 | | 3.195 | | 3.293 | | 3.396 |
| 均值 | 2.817 | | 3.066 | | 3.129 | | 3.178 | | 3.282 | | 3.420 |
| COV | 0.70% | | 0.44% | | 0.13% | | 0.38% | | 0.77% | | 0.51% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| P-1 | 样品8 | 1 | 3.076 | | 3.333 | | 3.414 | | 3.474 | | 3.589 | | 3.663 |
| 2 | 3.079 | | 3.337 | | 3.422 | | 3.481 | | 3.591 | | 3.672 |
| 3 | 3.083 | | 3.341 | | 3.424 | | 3.483 | | 3.592 | | 3.681 |
| 均值 | 3.079 | | 3.337 | | 3.420 | | 3.480 | | 3.590 | | 3.672 |
| COV | 0.10% | | 0.10% | | 0.13% | | 0.12% | | 0.04% | | 0.20% |
| P-2 | 样品8 | 1 | 3.184 | | 3.350 | | 3.426 | | 3.486 | | 3.589 | | 3.670 |
| 2 | 3.077 | | 3.330 | | 3.411 | | 3.469 | | 3.578 | | 3.659 |
| 3 | 3.082 | | 3.338 | | 3.421 | | 3.480 | | 3.589 | | 3.669 |
| 均值 | 3.114 | | 3.339 | | 3.419 | | 3.478 | | 3.585 | | 3.666 |
| COV | 1.57% | | 0.24% | | 0.18% | | 0.21% | | 0.14% | | 0.13% |
| G | 样品8 | 1 | 3.075 | | 3.323 | | 3.423 | | 3.453 | | 3.604 | | 3.661 |
| 2 | 3.061 | | 3.307 | | 3.394 | | 3.434 | | 3.584 | | 3.640 |
| 3 | 3.081 | | 3.321 | | 3.410 | | 3.450 | | 3.591 | | 3.647 |
| 均值 | 3.073 | | 3.317 | | 3.409 | | 3.446 | | 3.593 | | 3.650 |
| COV | 0.28% | | 0.22% | | 0.34% | | 0.24% | | 0.24% | | 0.24% |
| F | 样品8 | 1 | 3.020 | | 3.265 | | 3.354 | | 3.387 | | 3.534 | | 3.591 |
| 2 | 3.001 | | 3.248 | | 3.344 | | 3.368 | | 3.527 | | 3.590 |
| 3 | 3.031 | | 3.268 | | 3.339 | | 3.382 | | 3.547 | | 3.583 |
| 均值 | 3.017 | | 3.260 | | 3.346 | | 3.379 | | 3.536 | | 3.588 |
| COV | 0.41% | | 0.27% | | 0.19% | | 0.24% | | 0.23% | | 0.10% |
| B | 样品8 | 1 | 3.141 | | 3.344 | | 3.453 | | 3.641 | | 3.691 | | 3.652 |
| 2 | 3.116 | | 3.364 | | 3.502 | | 3.611 | | 3.662 | | 3.668 |
| 3 | 3.128 | | 3.389 | | 3.499 | | 3.637 | | 3.605 | | 3.769 |
| 均值 | 3.128 | | 3.366 | | 3.485 | | 3.629 | | 3.653 | | 3.696 |
| COV | 0.32% | | 0.54% | | 0.64% | | 0.37% | | 0.98% | | 1.40% |
| T | 样品8 | 1 | 3.108 | | 3.357 | | 3.483 | | 3.601 | | 3.627 | | 3.698 |
| 2 | 3.104 | | 3.354 | | 3.484 | | 3.605 | | 3.631 | | 3.704 |
| 3 | 3.113 | | 3.364 | | 3.491 | | 3.609 | | 3.635 | | 3.706 |
| 均值 | 3.108 | | 3.358 | | 3.486 | | 3.605 | | 3.631 | | 3.703 |
| COV | 0.11% | | 0.12% | | 0.11% | | 0.09% | | 0.09% | | 0.09% |
| N | 样品8 | 1 | 3.093 | | 3.376 | | 3.479 | | 3.526 | | 3.685 | | 3.752 |
| 2 | 3.097 | | 3.387 | | 3.491 | | 3.538 | | 3.693 | | 3.765 |
| 3 | 3.094 | | 3.382 | | 3.486 | | 3.533 | | 3.689 | | 3.762 |
| 均值 | 3.094 | | 3.382 | | 3.485 | | 3.533 | | 3.689 | | 3.759 |
| COV | 0.05% | | 0.13% | | 0.14% | | 0.14% | | 0.09% | | 0.15% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| A | 样品10 | 1 | 3.710 | | 3.985 | | 4.083 | | 4.127 | | 4.263 | | 4.325 |
| 2 | 3.710 | | 3.991 | | 4.086 | | 4.135 | | 4.268 | | 4.328 |
| 3 | 3.722 | | 4.003 | | 4.096 | | 4.146 | | 4.280 | | 4.340 |
| 均值 | 3.714 | | 3.993 | | 4.088 | | 4.136 | | 4.270 | | 4.331 |
| COV | 0.15% | | 0.19% | | 0.14% | | 0.19% | | 0.17% | | 0.15% |
| Q | 样品10 | 1 | 3.666 | | 3.926 | | 3.993 | | 4.008 | | 4.176 | | 4.213 |
| 2 | 3.670 | | 3.921 | | 4.002 | | 4.031 | | 4.153 | | 4.213 |
| 3 | 3.645 | | 3.910 | | 3.999 | | 4.023 | | 4.179 | | 4.222 |
| 均值 | 3.660 | | 3.919 | | 3.998 | | 4.021 | | 4.169 | | 4.216 |
| COV | 0.30% | | 0.17% | | 0.09% | | 0.24% | | 0.28% | | 0.10% |
| H-1 | 样品10 | 1 | 3.570 | | 3.830 | | 3.910 | | 3.960 | | 4.090 | | 4.150 |
| 2 | 3.600 | | 3.860 | | 3.940 | | 3.990 | | 4.130 | | 4.190 |
| 3 | 3.580 | | 3.840 | | 3.930 | | 3.960 | | 4.110 | | 4.170 |
| 均值 | 3.583 | | 3.843 | | 3.927 | | 3.970 | | 4.110 | | 4.170 |
| COV | 0.35% | | 0.32% | | 0.32% | | 0.36% | | 0.40% | | 0.39% |
| H-2 | 样品10 | 1 | 3.560 | | 3.820 | | 3.910 | | 3.950 | | 4.090 | | 4.150 |
| 2 | 3.570 | | 3.840 | | 3.930 | | 3.970 | | 4.110 | | 4.170 |
| 3 | 3.570 | | 3.840 | | 3.930 | | 3.960 | | 4.100 | | 4.160 |
| 均值 | 3.567 | | 3.833 | | 3.923 | | 3.960 | | 4.100 | | 4.160 |
| COV | 0.13% | | 0.25% | | 0.24% | | 0.21% | | 0.20% | | 0.20% |
| H-3 | 样品10 | 1 | 3.570 | | 3.830 | | 3.920 | | 3.960 | | 4.090 | | 4.160 |
| 2 | 3.570 | | 3.830 | | 3.920 | | 3.950 | | 4.100 | | 4.160 |
| 3 | 3.570 | | 3.840 | | 3.940 | | 3.960 | | 4.110 | | 4.160 |
| 均值 | 3.570 | | 3.833 | | 3.927 | | 3.957 | | 4.100 | | 4.160 |
| COV | 0.00% | | 0.12% | | 0.24% | | 0.12% | | 0.20% | | 0.00% |
| E | 样品10 | 1 | 3.530 | | 3.790 | | 3.900 | | 3.950 | | 4.070 | | 4.130 |
| 2 | 3.550 | | 3.800 | | 3.900 | | 3.960 | | 4.080 | | 4.140 |
| 3 | 3.540 | | 3.810 | | 3.900 | | 3.960 | | 4.070 | | 4.130 |
| 均值 | 3.540 | | 3.800 | | 3.900 | | 3.957 | | 4.073 | | 4.133 |
| COV | 0.23% | | 0.21% | | 0.00% | | 0.12% | | 0.12% | | 0.11% |
| C | 样品10 | 1 | 3.640 | | 3.920 | | 4.010 | | 4.050 | | / | | / |
| 2 | 3.640 | | 3.930 | | 4.020 | | 4.060 | | / | | / |
| 3 | 3.660 | | 3.950 | | 4.030 | | 4.080 | | / | | / |
| 均值 | 3.647 | | 3.933 | | 4.020 | | 4.063 | | / | | / |
| COV | 0.26% | | 0.32% | | 0.20% | | 0.31% | | / | | / |
| N | 样品10 | 1 | 3.625 | | 3.900 | | 3.997 | | 4.043 | | 4.175 | | 4.244 |
| 2 | 3.617 | | 3.896 | | 3.995 | | 4.042 | | 4.173 | | 4.245 |
| 3 | 3.620 | | 3.899 | | 3.995 | | 4.042 | | 4.172 | | 4.243 |
| 均值 | 3.621 | | 3.898 | | 3.996 | | 4.042 | | 4.173 | | 4.244 |
| COV | 0.09% | | 0.05% | | 0.02% | | 0.01% | | 0.03% | | 0.03% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| F | 样品11 | 1 | 3.612 | | 3.838 | | 3.907 | | 3.933 | | 4.068 | | 4.092 |
| 2 | 3.601 | | 3.826 | | 3.893 | | 3.935 | | 4.055 | | 4.107 |
| 3 | 3.618 | | 3.827 | | 3.880 | | 3.933 | | 4.069 | | 4.089 |
| 均值 | 3.610 | | 3.830 | | 3.893 | | 3.934 | | 4.064 | | 4.096 |
| COV | 0.20% | | 0.14% | | 0.28% | | 0.03% | | 0.16% | | 0.19% |
| B | 样品11 | 1 | 3.652 | | 3.876 | | 3.953 | | 3.984 | | 4.127 | | 4.231 |
| 2 | 3.679 | | 3.885 | | 3.956 | | 3.979 | | / | | / |
| 3 | 3.662 | | 3.885 | | 3.959 | | 3.967 | | / | | / |
| 均值 | 3.664 | | 3.882 | | 3.956 | | 3.977 | | 4.127 | | 4.231 |
| COV | 0.30% | | 0.11% | | 0.06% | | 0.18% | | / | | / |
| Q | 样品11 | 1 | 3.742 | | 3.943 | | 4.025 | | 4.027 | | 4.165 | | 4.213 |
| 2 | 3.741 | | 3.957 | | 4.005 | | 4.033 | | 4.176 | | 4.223 |
| 3 | 3.736 | | 3.952 | | 4.016 | | 4.025 | | 4.183 | | 4.211 |
| 均值 | 3.740 | | 3.951 | | 4.015 | | 4.028 | | 4.175 | | 4.216 |
| COV | 0.07% | | 0.15% | | 0.20% | | 0.08% | | 0.18% | | 0.12% |
| N | 样品11 | 1 | 3.709 | | 4.008 | | 4.111 | | 4.151 | | 4.334 | | 4.398 |
| 2 | 3.705 | | 4.002 | | 4.105 | | 4.145 | | 4.326 | | 4.390 |
| 3 | 3.699 | | 3.997 | | 4.100 | | 4.141 | | 4.322 | | 4.388 |
| 均值 | 3.704 | | 4.002 | | 4.106 | | 4.146 | | 4.327 | | 4.392 |
| COV | 0.11% | | 0.12% | | 0.11% | | 0.10% | | 0.11% | | 0.10% |
| D | 样品11 | 1 | 3.692 | | 3.936 | | 4.027 | | 4.072 | | 4.199 | | 4.268 |
| 2 | 3.692 | | 3.936 | | 4.026 | | 4.072 | | 4.198 | | 4.267 |
| 3 | 3.692 | | 3.940 | | 4.031 | | 4.076 | | 4.203 | | 4.271 |
| 均值 | 3.692 | | 3.937 | | 4.028 | | 4.073 | | 4.200 | | 4.269 |
| COV | 0.01% | | 0.04% | | 0.05% | | 0.05% | | 0.05% | | 0.05% |
| R | 样品11 | 1 | 3.523 | | 3.853 | | 3.922 | | 3.939 | | 4.147 | | 4.144 |
| 2 | 3.549 | | 3.836 | | 3.908 | | 3.927 | | 4.131 | | 4.151 |
| 3 | 3.564 | | 3.860 | | 3.950 | | 3.937 | | 4.100 | | 4.177 |
| 均值 | 3.545 | | 3.850 | | 3.927 | | 3.934 | | 4.126 | | 4.157 |
| COV | 0.47% | | 0.26% | | 0.44% | | 0.13% | | 0.47% | | 0.35% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 |
| G | 样品13 | 1 | 2.253 | | 2.355 | | 2.415 | | 2.454 | | 2.466 | | 2.493 |
| 2 | 2.258 | | 2.361 | | 2.409 | | 2.460 | | 2.473 | | 2.500 |
| 3 | 2.256 | | 2.360 | | 2.422 | | 2.460 | | 2.486 | | 2.513 |
| 均值 | 2.256 | | 2.359 | | 2.415 | | 2.458 | | 2.475 | | 2.502 |
| COV | 0.21% | | 0.26% | | 0.53% | | 0.28% | | 0.83% | | 0.83% |
| V | 样品13 | 1 | 2.252 | | 2.353 | | 2.408 | | 2.454 | | 2.475 | | 2.500 |
| 2 | 2.257 | | 2.357 | | 2.413 | | 2.457 | | 2.478 | | 2.503 |
| 3 | 2.250 | | 2.350 | | 2.403 | | 2.451 | | 2.472 | | 2.497 |
| 均值 | 2.253 | | 2.353 | | 2.408 | | 2.454 | | 2.475 | | 2.500 |
| COV | 0.29% | | 0.29% | | 0.41% | | 0.24% | | 0.24% | | 0.24% |
| A | 样品13 | 1 |  | |  | |  | |  | |  | |  |
| 2 |  | |  | |  | |  | |  | |  |
| 3 |  | |  | |  | |  | |  | |  |
| 均值 |  | |  | |  | |  | |  | |  |
| COV |  | |  | |  | |  | |  | |  |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 |
| G | 样品14 | 1 | 2.305 | | 2.388 | | 2.438 | | 2.478 | | 2.505 | | 2.519 |
| 2 | 2.302 | | 2.385 | | 2.435 | | 2.475 | | 2.501 | | 2.515 |
| 3 | 2.284 | | 2.378 | | 2.428 | | 2.468 | | 2.494 | | 2.508 |
| 均值 | 2.297 | | 2.384 | | 2.434 | | 2.474 | | 2.500 | | 2.514 |
| COV | 0.93% | | 0.42% | | 0.42% | | 0.42% | | 0.45% | | 0.45% |
| V | 样品14 | 1 | 2.297 | | 2.385 | | 2.433 | | 2.470 | | 2.488 | | 2.512 |
| 2 | 2.300 | | 2.388 | | 2.435 | | 2.474 | | 2.493 | | 2.513 |
| 3 | 2.297 | | 2.384 | | 2.433 | | 2.471 | | 2.491 | | 2.512 |
| 均值 | 2.298 | | 2.386 | | 2.434 | | 2.472 | | 2.491 | | 2.512 |
| COV | 0.14% | | 0.17% | | 0.09% | | 0.17% | | 0.21% | | 0.04% |
| A | 样品14 | 1 |  | |  | |  | |  | |  | |  |
| 2 |  | |  | |  | |  | |  | |  |
| 3 |  | |  | |  | |  | |  | |  |
| 均值 |  | |  | |  | |  | |  | |  |
|  |  | |  | |  | |  | |  | |  |

实验三：卸压测试条件下样品测试（手动）

如表9所示是不同实验室针对不同样品进行的压实密度测试的原始数据。同一实验室内，在各个压强下，三次测试结果的重复性较好。除个别实验室外，变异系数（COV）在1%以内。

表9 实验三条件下各实验室的压实密度原始数据（g/cm3）

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| L | 样品2 | 1 | 1.990 | 2.060 | | 2.100 | | 2.170 | | 2.180 | | 2.200 | |
| 2 | 1.980 | 2.060 | | 2.110 | | 2.180 | | 2.170 | | 2.190 | |
| 3 | 1.970 | 2.060 | | 2.100 | | 2.180 | | 2.170 | | 2.190 | |
| 均值 | 1.980 | 2.060 | | 2.103 | | 2.177 | | 2.173 | | 2.193 | |
| COV | 0.41% | 0.00% | | 0.22% | | 0.22% | | 0.22% | | 0.21% | |
| K | 样品2 | 1 | 1.959 | 2.083 | | 2.133 | | 2.174 | | 2.190 | | 2.188 | |
| 2 | 1.920 | 2.085 | | 2.134 | | 2.174 | | 2.189 | | 2.177 | |
| 3 | 1.987 | 2.085 | | 2.136 | | 2.167 | | 2.185 | | 2.152 | |
| 均值 | 1.955 | 2.084 | | 2.134 | | 2.172 | | 2.188 | | 2.172 | |
| COV | 1.41% | 0.05% | | 0.06% | | 0.15% | | 0.10% | | 0.69% | |
| S | 样品2 | 1 | 1.982 | 2.049 | | 2.095 | | 2.121 | | 2.136 | | 2.156 | |
| 2 | 1.984 | 2.057 | | 2.094 | | 2.125 | | 2.142 | | 2.161 | |
| 3 | 1.976 | 2.054 | | 2.091 | | 2.123 | | 2.134 | | 2.158 | |
| 均值 | 1.981 | 2.053 | | 2.094 | | 2.123 | | 2.137 | | 2.158 | |
| COV | 0.17% | 0.17% | | 0.08% | | 0.08% | | 0.16% | | 0.10% | |
| M | 样品2 | 1 | 2.030 | 2.120 | | 2.170 | | 2.200 | | 2.210 | | 2.230 | |
| 2 | 2.030 | 2.120 | | 2.180 | | 2.200 | | 2.200 | | 2.250 | |
| 3 | 2.020 | 2.120 | | 2.170 | | 2.200 | | 2.210 | | 2.240 | |
| 均值 | 2.027 | 2.120 | | 2.173 | | 2.200 | | 2.207 | | 2.240 | |
| COV | 0.23% | 0.00% | | 0.22% | | 0.00% | | 0.21% | | 0.36% | |
| O | 样品2 | 1 | 1.761 | 1.944 | | 2.054 | | 2.151 | | 2.180 | | 2.245 | |
| 2 | 1.775 | 1.948 | | 2.056 | | 2.151 | | 2.174 | | 2.238 | |
| 3 | 1.810 | 1.978 | | 2.087 | | 2.179 | | 2.204 | | 2.271 | |
| 均值 | 1.782 | 1.957 | | 2.065 | | 2.161 | | 2.186 | | 2.251 | |
| COV | 1.17% | 0.77% | | 0.73% | | 0.62% | | 0.59% | | 0.63% | |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| L | 样品9 | 1 | 2.930 | | 3.060 | | 3.110 | | 3.100 | | 3.240 | | / |
| 2 | 2.920 | | 3.060 | | 3.110 | | 3.110 | | 3.240 | | / |
| 3 | 2.920 | | 3.060 | | 3.100 | | 3.110 | | 3.240 | | / |
| 均值 | 2.923 | | 3.060 | | 3.107 | | 3.107 | | 3.240 | | / |
| COV | 0.16% | | 0.00% | | 0.15% | | 0.15% | | 0.00% | | / |
| K | 样品9 | 1 | 2.830 | | 3.075 | | 3.129 | | 3.138 | | 3.249 | | 3.274 |
| 2 | 2.899 | | 3.062 | | 3.114 | | 3.132 | | 3.247 | | 3.276 |
| 3 | 2.924 | | 3.068 | | 3.113 | | 3.132 | | 3.254 | | 3.268 |
| 均值 | 2.884 | | 3.068 | | 3.119 | | 3.134 | | 3.250 | | 3.273 |
| COV | 1.38% | | 0.17% | | 0.23% | | 0.09% | | 0.09% | | 0.10% |
| S | 样品9 | 1 | 2.907 | | 3.028 | | 3.071 | | 3.091 | | 3.180 | | 3.239 |
| 2 | 2.898 | | 3.021 | | 3.071 | | 3.103 | | 3.194 | | 3.235 |
| 3 | 2.903 | | 3.030 | | 3.064 | | 3.100 | | 3.186 | | 3.238 |
| 均值 | 2.903 | | 3.026 | | 3.069 | | 3.098 | | 3.187 | | 3.238 |
| COV | 0.13% | | 0.11% | | 0.11% | | 0.16% | | 0.19% | | 0.06% |
| M | 样品9 | 1 | 2.940 | | 3.080 | | 3.130 | | 3.140 | | 3.260 | | 3.290 |
| 2 | 2.940 | | 3.080 | | 3.120 | | 3.140 | | 3.260 | | 3.300 |
| 3 | 2.940 | | 3.080 | | 3.120 | | 3.150 | | 3.280 | | 3.300 |
| 均值 | 2.940 | | 3.080 | | 3.123 | | 3.143 | | 3.267 | | 3.297 |
| COV | 0.00% | | 0.00% | | 0.15% | | 0.15% | | 0.29% | | 0.14% |
| O | 样品9 | 1 | 2.631 | | 2.866 | | 2.966 | | 2.992 | | 3.242 | | 3.335 |
| 2 | 2.654 | | 2.881 | | 2.977 | | 3.003 | | 3.246 | | 3.347 |
| 3 | 2.670 | | 2.903 | | 2.996 | | 3.028 | | 3.273 | | 3.366 |
| 均值 | 2.652 | | 2.883 | | 2.979 | | 3.008 | | 3.254 | | 3.349 |
| COV | 0.61% | | 0.52% | | 0.41% | | 0.49% | | 0.41% | | 0.38% |
| 实验室 | 样品 | 次数 | 压强（Mpa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| L | 样品12 | 1 | 3.600 | | 3.790 | | 3.830 | | 3.890 | | 4.050 | | 4.100 |
| 2 | 3.600 | | 3.790 | | 3.830 | | 3.890 | | 4.050 | | 4.100 |
| 3 | 3.600 | | 3.790 | | 3.830 | | 3.890 | | 4.050 | | 4.110 |
| 均值 | 3.600 | | 3.790 | | 3.830 | | 3.890 | | 4.050 | | 4.103 |
| COV | 0.00% | | 0.00% | | 0.00% | | 0.00% | | 0.00% | | 0.11% |
| K | 样品12 | 1 | 3.503 | | 3.846 | | 3.918 | | 3.955 | | 4.096 | | 4.045 |
| 2 | 3.330 | | 3.803 | | 3.906 | | 3.922 | | 4.084 | | 4.063 |
| 3 | 3.331 | | 3.812 | | 3.914 | | 3.942 | | 4.071 | | 4.035 |
| 均值 | 3.388 | | 3.820 | | 3.913 | | 3.940 | | 4.084 | | 4.048 |
| COV | 2.40% | | 0.48% | | 0.13% | | 0.34% | | 0.25% | | 0.29% |
| S | 样品12 | 1 | 3.536 | | 3.777 | | 3.820 | | 3.838 | | 3.947 | | 4.007 |
| 2 | 3.548 | | 3.760 | | 3.820 | | 3.838 | | 3.936 | | 4.002 |
| 3 | 3.544 | | 3.779 | | 3.825 | | 3.842 | | 3.945 | | 4.000 |
| 均值 | 3.543 | | 3.772 | | 3.822 | | 3.839 | | 3.943 | | 4.003 |
| COV | 0.14% | | 0.23% | | 0.05% | | 0.05% | | 0.12% | | 0.08% |
| M | 样品12 | 1 | 3.580 | | 3.820 | | 3.880 | | 3.880 | | 4.030 | | 4.080 |
| 2 | 3.600 | | 3.810 | | 3.890 | | 3.930 | | 4.030 | | 4.070 |
| 3 | 3.580 | | 3.820 | | 3.890 | | 3.900 | | 4.030 | | 4.070 |
| 均值 | 3.587 | | 3.817 | | 3.887 | | 3.903 | | 4.030 | | 4.073 |
| COV | 0.26% | | 0.12% | | 0.12% | | 0.53% | | 0.00% | | 0.12% |
| O | 样品12 | 1 | 3.191 | | 3.544 | | 3.670 | | 3.701 | | 4.010 | | 4.118 |
| 2 | 3.196 | | 3.561 | | 3.684 | | 3.719 | | 4.024 | | 4.128 |
| 3 | 3.185 | | 3.565 | | 3.694 | | 3.730 | | 4.039 | | 4.153 |
| 均值 | 3.190 | | 3.556 | | 3.683 | | 3.716 | | 4.024 | | 4.133 |
| COV | 0.14% | | 0.26% | | 0.27% | | 0.32% | | 0.29% | | 0.36% |

**3.3.5试验数据分析**

实验一：加压测试条件下样品测试（自动）

鉴于各实验室内测试的重复性较好，故在此取各实验室平均值进行汇总。由表10可知在加压条件下各厂家的压实密度均值差异较大，尤其在高压强下明显分为两个区间，数值之差甚至达到0.5g/cm2。

编制组经过调研和实验分析知，行业内现有的全自动测试设备对于模具形变的补偿方式不同是造成这一差距的主要原因。比如有些设备通过小压力下的模具复位来进行厚度零点选取，即无论采用多大的压力进行测试，零点皆为小压力下的模具厚度数值，忽略了模具在高压强下的形变。而有些厂家的设备通过测试不同压强下模具的形变，内置补偿基线，对每个压力点进行了厚度补偿。这直接导致了测试数据较未补偿的偏小。实验室V调取了补偿前和补偿后的原始数据，如下表中，实验室V-2是补偿前数据，实验室V-1是补偿后数据。对比可知，补偿前数据与单点零点选择的设备接近。

基于上述实验数据，在加压法测试模式下，必须明确设备的补偿方式，是单点补偿或是基线补偿。只有相同的补偿方式计算得数值才具有可比性。因此表10中将两种零点取值方式进行了区分。

表10 实验一条件下各实验室的压实密度均值（g/cm3）

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 实验室 | 样品/补偿方式 | 压强（MPa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| G | 样品1/单点 | 2.080 | 2.227 | | 2.320 | | 2.396 | | 2.417 | | 2.468 | |
| H-1 | 2.070 | 2.250 | | 2.367 | | 2.477 | | 2.503 | | 2.580 | |
| H-2 | 2.063 | 2.243 | | 2.357 | | 2.463 | | 2.493 | | 2.567 | |
| E | 2.123 | 2.273 | | 2.373 | | 2.447 | | 2.483 | | 2.537 | |
| V-2 | 1.990 | 2.157 | | 2.263 | | 2.363 | | 2.389 | | 2.457 | |
| A | 2.263 | 2.389 | | 2.459 | | 2.519 | | 2.552 | | 2.588 | |
| COV | | 4.0% | 3.1% | | 2.5% | | 2.1% | | 2.2% | | 2.1% | |
| C | 样品1/基线 | 2.030 | 2.160 | | 2.230 | | 2.290 | | 2.300 | | / | |
| T | 2.004 | 2.125 | | 2.191 | | 2.245 | | 2.258 | | 2.293 | |
| V-1 | 1.990 | 2.102 | | 2.161 | | 2.209 | | 2.220 | | 2.249 | |
| COV | | 0.8% | 1.1% | | 1.3% | | 1.5% | | 1.4% | | 1.0% | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| G | 样品3/单点 | 2.174 | 2.331 | | 2.424 | | 2.508 | | 2.530 | | 2.582 | |
| H-1 | 2.217 | 2.393 | | 2.510 | | 2.640 | | 2.667 | | 2.747 | |
| H-2 | 2.193 | 2.390 | | 2.517 | | 2.640 | | 2.670 | | 2.750 | |
| E | 2.213 | 2.367 | | 2.470 | | 2.557 | | 2.587 | | 2.637 | |
| A | 2.393 | 2.523 | | 2.602 | | 2.671 | | 2.700 | | 2.737 | |
| V-2 | 2.064 | 2.229 | | 2.338 | | 2.440 | | 2.468 | | 2.538 | |
| COV | | 4.4% | 3.7% | | 3.3% | | 3.2% | | 3.2% | | 3.2% | |
| T | 样品3/基线 | 2.100 | 2.218 | | 2.285 | | 2.341 | | 2.353 | | 2.390 | |
| C | 2.103 | 2.233 | | 2.300 | | 2.357 | | 2.373 | | / | |
| V-1 | 2.064 | 2.170 | | 2.228 | | 2.277 | | 2.287 | | 2.316 | |
| COV | | 0.9% | 1.2% | | 1.4% | | 1.5% | | 1.6% | | 1.6% | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| R | 样品4/单点 | 1.945 | 2.032 | | 2.141 | | 2.227 | | 2.260 | | 2.286 | |
| P | 2.173 | 2.320 | | 2.411 | | 2.495 | | 2.532 | | 2.578 | |
| COV | | 5.5% | 6.6% | | 5.9% | | 5.7% | | 5.7% | | 6.0% | |
| T | 样品4/基线 | 2.069 | 2.184 | | 2.251 | | 2.305 | | 2.319 | | 2.352 | |
| N | 2.080 | 2.193 | | 2.258 | | 2.313 | | 2.323 | | 2.360 | |
| D | 2.092 | 2.211 | | 2.277 | | 2.333 | | 2.346 | | 2.382 | |
| COV | | 0.4% | 0.5% | | 0.5% | | 0.5% | | 0.5% | | 0.5% | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 | |
| G | 样品5/单点 | 3.141 | 3.499 | | 3.617 | | 3.651 | | 3.911 | | 3.993 | |
| H-1 | 3.137 | 3.550 | | 3.697 | | 3.740 | | 4.077 | | 4.197 | |
| H-2 | 3.114 | 3.528 | | 3.673 | | 3.714 | | 4.057 | | 4.177 | |
| H-3 | 3.100 | 3.517 | | 3.660 | | 3.703 | | 4.040 | | 4.160 | |
| H-4 | 3.073 | 3.483 | | 3.623 | | 3.663 | | 4.003 | | 4.123 | |
| E | 3.120 | 3.473 | | 3.600 | | 3.657 | | 3.870 | | 3.963 | |
| Q | 3.139 | 3.498 | | 3.566 | | 3.589 | | 3.802 | | 3.880 | |
| V-2 | 3.061 | 3.458 | | 3.589 | | 3.623 | | 3.930 | | 4.035 | |
| COV | | 0.9% | 0.8% | | 1.2% | | 1.3% | | 2.3% | | 2.7% | |
| C | 样品5/基线 | 3.130 | 3.477 | | 3.580 | | 3.610 | | / | | / | |
| V-1 | 3.061 | 3.361 | | 3.443 | | 3.463 | | 3.620 | | 3.665 | |
| COV | | 1.1% | 1.7% | | 1.9% | | 2.1% | | / | | / | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| F | 样品6/单点 | 3.002 | | 3.272 | | 3.292 | | 3.464 | | 3.751 | | 3.844 |
| Q | 3.073 | | 3.306 | | 3.378 | | 3.421 | | 3.613 | | 3.664 |
| COV | | 1.2% | | 0.5% | | 1.3% | | 0.6% | | 1.9% | | 2.4% |
| D | 样品6/基线 | 2.990 | | 3.235 | | 3.320 | | 3.343 | | 3.541 | | 3.607 |
| COV | | / | | / | | / | | / | | / | | / |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| F | 样品7/单点 | 3.002 | | 3.275 | | 3.379 | | 3.403 | | 3.751 | | 3.859 |
| B | 3.148 | | 3.462 | | 3.696 | | 3.879 | | 3.980 | | 4.191 |
| COV | | 2.4% | | 2.8% | | 4.5% | | 6.5% | | 3.0% | | 4.1% |
| P | 样品7/基线 | 3.068 | | 3.310 | | 3.422 | | 3.478 | | 3.671 | | 3.766 |
| D | 3.001 | | 3.252 | | 3.347 | | 3.373 | | 3.603 | | 3.680 |
| COV | | 1.1% | | 0.9% | | 1.1% | | 1.5% | | 0.9% | | 1.2% |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| P-1 | 样品8/单点 | 3.197 | | 3.504 | | 3.560 | | 3.680 | | 3.881 | | 3.977 |
| P-2 | 3.231 | | 3.499 | | 3.617 | | 3.672 | | 3.872 | | 3.960 |
| G | 3.158 | | 3.486 | | 3.602 | | 3.636 | | 3.895 | | 3.984 |
| F | 3.121 | | 3.509 | | 3.652 | | 3.702 | | 4.029 | | 4.146 |
| B | 3.148 | | 3.462 | | 3.696 | | 3.879 | | 3.980 | | 4.191 |
| COV | | 1.2% | | 0.5% | | 1.3% | | 2.3% | | 1.6% | | 2.4% |
| T | 样品8/基线 | 3.089 | | 3.391 | | 3.492 | | 3.517 | | 3.725 | | 3.787 |
| N | 3.157 | | 3.501 | | 3.609 | | 3.635 | | 3.843 | | 3.902 |
| COV | | 1.1% | | 1.6% | | 1.6% | | 1.7% | | 1.6% | | 1.5% |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| Q | 样品10/单点 | 3.756 | | 4.107 | | 4.224 | | 4.249 | | 4.495 | | 4.573 |
| H-1 | 3.703 | | 4.147 | | 4.307 | | 4.347 | | 4.733 | | 4.880 |
| H-2 | 3.710 | | 4.157 | | 4.313 | | 4.363 | | 4.753 | | 4.893 |
| H-3 | 3.707 | | 4.150 | | 4.307 | | 4.353 | | 4.737 | | 4.883 |
| E | 3.693 | | 4.083 | | 4.217 | | 4.270 | | 4.533 | | 4.623 |
| V-2 | 3.588 | | 3.989 | | 4.133 | | 4.176 | | 4.524 | | 4.649 |
| COV | | 1.4% | | 1.4% | | 1.5% | | 1.6% | | 2.4% | | 2.9% |
| C | 样品10/基线 | 3.677 | | 4.007 | | 4.110 | | 4.137 | | / | | / |
| N | 3.634 | | 3.963 | | 4.069 | | 4.097 | | 4.313 | | 4.380 |
| V-1 | 3.588 | | 3.860 | | 3.942 | | 3.964 | | 4.119 | | 4.163 |
| COV | | 1.0% | | 1.6% | | 1.8% | | 1.8% | | 2.3% | | 2.5% |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| F | 样品11/单点 | 3.749 | | 4.152 | | 4.291 | | 4.345 | | 4.715 | | 4.833 |
| B | 3.572 | | 3.933 | | 4.204 | | 4.434 | | 4.573 | | 4.840 |
| Q | 3.847 | | 4.151 | | 4.250 | | 4.276 | | 4.526 | | 4.577 |
| COV | | 3.1% | | 2.5% | | 0.8% | | 1.5% | | 1.7% | | 2.6% |
| N | 样品11/基线 | 3.702 | | 3.998 | | 4.093 | | 4.117 | | 4.321 | | 4.384 |
| D | 3.734 | | 4.043 | | 4.144 | | 4.172 | | 4.398 | | 4.473 |
| COV | | 1.6% | | 2.3% | | 2.5% | | 2.8% | | 3.9% | | 4.4% |

实验二：卸压测试条件下样品测试（自动）

鉴于各实验室内测试的重复性较好，故在此取各实验室平均值进行汇总，计算实验室间的变异系数(实验室A的样品1与样品3的数据与其他实验室差距较大，不列入统计)。由如下数据可知，卸压到5MPa时，在测试的各个压强下，COV值主要集中在1.0~2.0%。此外，加压模式下存在的设备零点取值差异造成的组间偏差在卸压模式下影响较小。

表11 实验二条件下各实验室的压实密度均值（g/cm3）

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | | 188.44 | | | 199.75 | | | | 226.13 | | |
| G | 样品1 | 1.970 | 2.063 | | 2.117 | | | 2.167 | | | 2.186 | | | | 2.208 | | |
| H-1 | 1.943 | 2.033 | | 2.087 | | | 2.133 | | | 2.157 | | | | 2.183 | | |
| H-2 | 1.953 | 2.047 | | 2.097 | | | 2.147 | | | 2.177 | | | | 2.197 | | |
| E | 1.987 | 2.083 | | 2.133 | | | 2.183 | | | 2.207 | | | | 2.233 | | |
| C | 2.000 | 2.107 | | 2.167 | | | 2.217 | | | 2.240 | | | | / | | |
| T | 1.982 | 2.125 | | 2.193 | | | 2.257 | | | 2.270 | | | | 2.310 | | |
| COV | | 1.0% | 1.5% | | 1.8% | | | 1.9% | | | 1.8% | | | | 2.0% | | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | | 188.44 | | | 199.75 | | | | 226.13 | | |
| G | 样品3 | 2.082 | 2.180 | | 2.240 | | | 2.288 | | | 2.307 | | | | 2.334 | | |
| H-1 | 2.067 | 2.167 | | 2.227 | | | 2.277 | | | 2.297 | | | | 2.327 | | |
| H-2 | 2.063 | 2.170 | | 2.223 | | | 2.273 | | | 2.300 | | | | 2.330 | | |
| E | 2.080 | 2.177 | | 2.237 | | | 2.280 | | | 2.307 | | | | 2.333 | | |
| T | 2.058 | 2.178 | | 2.239 | | | 2.300 | | | 2.314 | | | | 2.351 | | |
| C | 2.083 | 2.190 | | 2.250 | | | 2.300 | | | 2.320 | | | | / | | |
| COV | | 0.5% | 0.3% | | 0.4% | | | 0.5% | | | 0.3% | | | | 0.4% | | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 113.07 | 150.76 | | | 188.44 | | | 199.75 | | | | 226.13 | | | |
| R | 样品4 | 1.945 | 2.032 | 2.141 | | | 2.227 | | | 2.260 | | | | 2.286 | | | |
| P | 2.040 | 2.134 | 2.190 | | | 2.259 | | | 2.269 | | | | 2.298 | | | |
| T | 2.038 | 2.157 | 2.219 | | | 2.278 | | | 2.291 | | | | 2.329 | | | |
| N | 2.056 | 2.161 | 2.222 | | | 2.274 | | | 2.297 | | | | 2.326 | | | |
| D | 2.067 | 2.170 | 2.233 | | | 2.285 | | | 2.308 | | | | 2.336 | | | |
| COV | | 2.1% | 2.4% | 1.5% | | | 0.9% | | | 0.8% | | | | 0.8% | | | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 150.76 | | | 188.44 | | | 199.75 | | | | 301.51 | | | | 339.2 |
| A | 样品5 | 3.048 | 3.335 | | | 3.434 | | | 3.474 | | | | 3.619 | | | | 3.680 |
| G | 3.043 | 3.311 | | | 3.399 | | | 3.442 | | | | 3.582 | | | | 3.634 |
| H-1 | 3.017 | 3.290 | | | 3.383 | | | 3.423 | | | | 3.573 | | | | 3.637 |
| H-2 | 3.020 | 3.303 | | | 3.400 | | | 3.443 | | | | 3.593 | | | | 3.650 |
| H-3 | 2.990 | 3.270 | | | 3.363 | | | 3.407 | | | | 3.560 | | | | 3.617 |
| H-4 | 2.967 | 3.243 | | | 3.337 | | | 3.373 | | | | 3.523 | | | | 3.583 |
| E | 3.003 | 3.277 | | | 3.367 | | | 3.413 | | | | 3.537 | | | | 3.593 |
| Q | 3.062 | 3.356 | | | 3.402 | | | 3.418 | | | | 3.569 | | | | 3.617 |
| C | 3.077 | 3.387 | | | 3.487 | | | 3.527 | | | | / | | | | / |
| COV | | 1.1% | 1.3% | | | 1.2% | | | 1.2% | | | | 0.8% | | | | 0.8% |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 150.76 | | | 188.44 | | | 199.75 | | | | 301.51 | | | | 339.2 |
| F | 样品6 | 2.903 | 3.054 | | | 3.067 | | | 3.161 | | | | 3.290 | | | | 3.324 |
| B | 2.941 | 3.141 | | | 3.205 | | | 3.226 | | | | 3.361 | | | | 3.397 |
| Q | 3.000 | 3.158 | | | 3.209 | | | 3.234 | | | | 3.359 | | | | 3.390 |
| D | 2.946 | 3.149 | | | 3.231 | | | 3.274 | | | | 3.397 | | | | 3.465 |
| R | 2.800 | 3.043 | | | 3.164 | | | 3.224 | | | | 3.293 | | | | 3.375 |
| COV | | 2.3% | 1.6% | | | 1.8% | | | 1.1% | | | | 1.3% | | | | 1.3% |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 150.76 | | | 188.44 | | | 199.75 | | | | 301.51 | | | | 339.2 |
| F | 样品7 | 2.898 | 3.047 | | | 3.092 | | | 3.101 | | | | 3.287 | | | | 3.325 |
| B | 2.909 | 3.030 | | | 3.151 | | | 3.207 | | | | 3.223 | | | | 3.291 |
| P | 2.964 | 3.142 | | | 3.219 | | | 3.277 | | | | 3.382 | | | | 3.462 |
| D | 2.967 | 3.169 | | | 3.259 | | | 3.307 | | | | 3.447 | | | | 3.524 |
| R | 2.817 | 3.066 | | | 3.129 | | | 3.178 | | | | 3.282 | | | | 3.420 |
| COV | | 1.9% | 1.8% | | | 1.9% | | | 2.3% | | | | 2.4% | | | | 2.5% |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 150.76 | | | 188.44 | | | 199.75 | | | 301.51 | | | | 339.2 | |
| P-1 | 样品8 | 3.079 | 3.337 | | | 3.420 | | | 3.480 | | | 3.590 | | | | 3.672 | |
| P-2 | 3.114 | 3.339 | | | 3.419 | | | 3.478 | | | 3.585 | | | | 3.666 | |
| G | 3.073 | 3.317 | | | 3.409 | | | 3.446 | | | 3.593 | | | | 3.650 | |
| F | 3.017 | 3.260 | | | 3.346 | | | 3.379 | | | 3.536 | | | | 3.588 | |
| B | 3.128 | 3.366 | | | 3.485 | | | 3.629 | | | 3.653 | | | | 3.696 | |
| T | 3.108 | 3.358 | | | 3.486 | | | 3.605 | | | 3.631 | | | | 3.703 | |
| N | 3.094 | 3.382 | | | 3.485 | | | 3.533 | | | 3.689 | | | | 3.759 | |
| COV | | 1.1% | 1.1% | | | 1.4% | | | 2.3% | | | 1.3% | | | | 1.3% | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 150.76 | | | 188.44 | | | 199.75 | | | 301.51 | | | | 339.2 | |
| A | 样品10 | 3.714 | 3.993 | | | 4.088 | | | 4.136 | | | 4.270 | | | | 4.331 | |
| Q | 3.660 | 3.919 | | | 3.998 | | | 4.021 | | | 4.169 | | | | 4.216 | |
| H-1 | 3.583 | 3.843 | | | 3.927 | | | 3.970 | | | 4.110 | | | | 4.170 | |
| H-2 | 3.567 | 3.833 | | | 3.923 | | | 3.960 | | | 4.100 | | | | 4.160 | |
| H-3 | 3.570 | 3.833 | | | 3.927 | | | 3.957 | | | 4.100 | | | | 4.160 | |
| E | 3.540 | 3.800 | | | 3.900 | | | 3.957 | | | 4.073 | | | | 4.133 | |
| C | 3.647 | 3.933 | | | 4.020 | | | 4.063 | | | / | | | | / | |
| N | 3.621 | 3.898 | | | 3.996 | | | 4.042 | | | 4.173 | | | | 4.244 | |
| COV | | 1.5% | 1.6% | | | 1.5% | | | 1.5% | | | 1.5% | | | | 1.5% | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 150.76 | | | 188.44 | | | 199.75 | | | 301.51 | | | | 339.2 | |
| F | 样品11 | 3.610 | 3.830 | | | 3.893 | | | 3.934 | | | 4.064 | | | | 4.096 | |
| B | 3.664 | 3.882 | | | 3.956 | | | 3.977 | | | 4.127 | | | | 4.231 | |
| Q | 3.740 | 3.951 | | | 4.015 | | | 4.028 | | | 4.175 | | | | 4.216 | |
| N | 3.704 | 4.002 | | | 4.106 | | | 4.146 | | | 4.327 | | | | 4.392 | |
| D | 3.692 | 3.937 | | | 4.028 | | | 4.073 | | | 4.200 | | | | 4.269 | |
| R | 3.545 | 3.850 | | | 3.927 | | | 3.934 | | | 4.126 | | | | 4.157 | |
| COV | | 1.8% | 1.5% | | | 1.8% | | | 1.9% | | | 2.0% | | | | 2.2% | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 113.07 | | | 150.76 | | | 188.44 | | | 199.75 | | | | 226.13 | |
| G | 样品13 | 2.256 | 2.359 | | | 2.415 | | | 2.458 | | | 2.475 | | | | 2.502 | |
| A | 2.253 | 2.353 | | | 2.408 | | | 2.454 | | | 2.475 | | | | 2.500 | |
| V |  |  | | |  | | |  | | |  | | | |  | |
| COV | | 0.13% | 0.27% | | | 0.37% | | | 0.20% | | | 0.00% | | | | 0.10% | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | | | | | | |
| 63.32 | 113.07 | | | 150.76 | | | 188.44 | | | 199.75 | | | | 226.13 | |
| G | 样品14 | 2.297 | 2.384 | | | 2.434 | | | 2.474 | | | 2.500 | | | | 2.514 | |
| A | 2.298 | 2.386 | | | 2.434 | | | 2.472 | | | 2.491 | | | | 2.512 | |
| V |  |  | | |  | | |  | | |  | | | |  | |
| COV | | 0.05% | 0.10% | | | 0.00% | | | 0.10% | | | 0.47% | | | | 0.10% | |

实验三：卸压测试条件下样品测试（手动）

鉴于各实验室的三次平行测试的重复性较好，故在此取各实验室平均值进行汇总，计算实验室间的变异系数。由如下数据可知，在63.32MPa和113.07MPa压强下，实验室O测试数据与其他实验室存在明显的系统性偏差，导致COV值较大（>2%），而压强≥150.76MPa时，COV值主要集中在1.0~2.0%。

表12 实验三条件下各实验室的压实密度均值（g/cm3）

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | 113.07 | | 150.76 | | 188.44 | | 199.75 | | 226.13 | |
| L | 样品2 | 1.980 | 2.060 | | 2.103 | | 2.177 | | 2.173 | | 2.193 | |
| K | 1.955 | 2.084 | | 2.134 | | 2.172 | | 2.188 | | 2.172 | |
| S | 1.981 | 2.053 | | 2.094 | | 2.123 | | 2.137 | | 2.158 | |
| M | 2.027 | 2.120 | | 2.173 | | 2.200 | | 2.207 | | 2.240 | |
| O | 1.782 | 1.957 | | 2.065 | | 2.161 | | 2.186 | | 2.251 | |
| COV | | 4.4% | 2.6% | | 1.7% | | 1.2% | | 1.1% | | 1.7% | |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| L | 样品9 | 2.923 | | 3.060 | | 3.107 | | 3.107 | | 3.240 | | / |
| K | 2.884 | | 3.068 | | 3.119 | | 3.134 | | 3.250 | | 3.273 |
| S | 2.903 | | 3.026 | | 3.069 | | 3.098 | | 3.187 | | 3.238 |
| M | 2.940 | | 3.080 | | 3.123 | | 3.143 | | 3.267 | | 3.297 |
| O | 2.652 | | 2.883 | | 2.979 | | 3.008 | | 3.254 | | 3.349 |
| COV | | 3.6% | | 2.2% | | 1.6% | | 1.4% | | 0.9% | | 1.4% |
| 实验室 | 样品 | 压强（MPa） | | | | | | | | | | |
| 63.32 | | 150.76 | | 188.44 | | 199.75 | | 301.51 | | 339.2 |
| L | 样品12 | 3.600 | | 3.790 | | 3.830 | | 3.890 | | 4.050 | | 4.103 |
| K | 3.388 | | 3.820 | | 3.913 | | 3.940 | | 4.084 | | 4.048 |
| S | 3.543 | | 3.772 | | 3.822 | | 3.839 | | 3.943 | | 4.003 |
| M | 3.587 | | 3.817 | | 3.887 | | 3.903 | | 4.030 | | 4.073 |
| O | 3.190 | | 3.556 | | 3.683 | | 3.716 | | 4.024 | | 4.133 |
| COV | | 4.5% | | 2.6% | | 2.1% | | 2.0% | | 1.2% | | 1.1% |

**3.3.6 试验小结与允许差确定**

允许差设定如下：

表13 测试允许差

|  |  |  |  |
| --- | --- | --- | --- |
| 方法 | 允许差 | 同一实验室 | 不同实验室 |
| 自动加压 | 压实密度（g/cm3） | 0.05 | 0.2 |
| 自动泄压 | 0.05 | 0.06 |
| 手动泄压 | 0.05 | 0.06 |

**四、标准中涉及的专利情况**

本文件不涉及专利问题。

**五、标准预期达到的社会效益等情况**

**5.1 标准编写的目的和意义**

锂电行业的飞速发展和壮大势必推动标准化工作的加速开展以此促进行业的规范和健康运行。锂离子电池的能量密度一直是大家关注的焦点。锂离子电池正负极极片的压实密度对制成后电池的比能量、内阻、循环性能、电解液浸润性等一系列参数有直接的影响，而正负极粉末的压实密度直接影响电池极片的压实密度，因此正负极粉末压实密度是一个必要的检测参数。随着用户对锂离子电池体系能量密度的要求越来越高，即对单体电池的比容量要求越来越高，也使市场对正负极粉末压实密度提出更高要求。当前锂电行业相关标准主要集中在电芯、材料制造和工艺等方面，针对锂电材料测试表征的标准极少，有必要进行补充和完善。目前正负极粉末压实密度的测试方法不统一，相关的测试标准较少，企业间对标困难。目前国内多数公司在测试时使用的压强较低，在低测试压强下，粉末间存在较多空隙，材料接触不充分，会导致测试误差较大，数据可靠性较低。国外有锂电企业表征正负极材料密度采用振实/堆积密度方法，但该方法依旧存在颗粒空隙较大导致的接触不充分，无法真实表征颗粒在极片中的受压状态。

本文件的建立会使得锂电行业对粉末压实密度的测试方法形成统一的标准，进而提高测试结果的可靠性，极大的减少了由于企业间对标而产生的时间及金钱的浪费，减少了因数据偏差而导致的争端。

**5.2 标准预期的作用和效益**

本文件充分考虑了目前国内锂离子电池材料生产、研发、应用和检测的实际技术水平。本文件颁布执行后，将在国内形成对锂电材料的压实密度的统一的分析测试标准，能够加强企业和各研究机构测试之间的可靠性和可比性，助力我国锂离子电池产业的发展，提高国内企业在国际市场发展力和竞争力。

**六、采用国际标准和国外先进标准的情况**

经查询，本文件与国内外现行标准及制定中的标准无重复交叉情况。

**七、与现行法律、法规、强制性国家标准及相关标准协调配套情况**

本文件与有关的现行法律、法规和强制性国家标准没有冲突。

**八、重大分歧意见的处理经过和依据**

无。

**九、标准作为强制性或推荐性标准的建议**

建议本文件为推荐性国家标准，供相关组织参考采用。

**十、贯彻标准的要求和措施建议**

建议向锂电材料及电池研发、生产、销售、检测的相关企业和单位积极贯彻本文件的内容。

**十一、废止现行有关标准的建议**

无。

**十二、其他应予说明的事项**

无。

《锂离子电池材料 粉末压实密度的测定》标准编制组

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