

碱矿渣水泥与混凝土

蒲心诚 著

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内 容 简 介

本书论述了碱矿渣水泥与混凝土的基本原理、原材料及其结构、性能、应用情况和未来发展前景。与当前普遍应用的硅酸盐水泥与混凝土相比,碱矿渣水泥与混凝土具有性能优异、原料广泛、工艺简单、节约能源、投资少、成本低及环保性强等优势,是一种极具开发价值和推广应用价值的水泥与混凝土新品种。

本书适合土木工程领域与建筑材料行业的工程师及专业技术人员、科研机构的研究工作者、高等学校的教师及本科生和研究生阅读,也适合广大企业家及各级政府主管部门的领导者研读。

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前 言

1984年,作者在重庆建筑工程学院图书馆发现一本名为“碱矿渣细粒混凝土”的俄文版科技专著(即文献[12])。读后,极感振奋,原来除了常用的硅酸盐水泥与混凝土以外,这世上还存在另外一种优秀的水泥与混凝土,不但水硬性极佳,而且可以达到甚高的强度,各项耐久性指标都十分优异。不仅如此,这种水泥混凝土还具有许多技术和经济上的优势,如原料广泛、成本低廉、工艺简单、投资较少、能耗较低、环保性强等。这本专著深深吸引了作者,把作者带入碱矿渣水泥与混凝土这一研究领域。此后,作者经过两年半的努力,终于获得成功,制成了集快硬、高强、低热、高抗渗、高抗冻、高抗蚀于一体的碱矿渣混凝土,并在原重庆建筑工程学院大型混凝土工艺实验室制备了大批碱矿渣混凝土构件。1987年6月由重庆市科学技术委员会组织了“碱矿渣(JK)混凝土研究项目”技术鉴定。随后,向国家自然科学基金委员会、建设部、国家建材局等部门申请并获准了多项科研项目,以便继续深入研究,重点解决了以硅酸钠为碱组分的碱矿渣水泥与混凝土凝结时间过短的难题。1991年8月又由重庆市科学技术委员会组织了“碱矿渣(JK)高级水泥研究项目”的技术鉴定。1998年5月再由重庆市科学技术委员会主持鉴定了“新一代(中性钠盐)碱矿渣水泥”研究项目。这些成果达到了当时的国际先进水平。

1990年,作者为了加强国际交流,进一步向碱矿渣水泥的发明者学习,致函苏联乌克兰基辅建筑工程学院 Глуховский 教授,邀请他来华讲学。不幸的是,教授刚刚辞世,其大弟子 Кривенко 教授代为回函,并表示愿意来华访问。于是,Кривенко 教授应邀于1990年来重庆讲学一周,内容十分丰富,并馈赠作者许多碱矿渣水泥与混凝土领域的宝贵研究资料。1992年10月,作者回访了乌克兰基辅建筑工程学院,并交流研究成果。此后,Кривенко 教授又两度访问重庆。

本书即根据作者及合作者的研究成果,以及原苏联、欧美国家相关文献编写而成。

碱矿渣水泥发明于1957年,起初被称为“土壤水泥”,用其制成的混凝土称为“土壤硅酸盐”,20世纪70年代,更名为“碱矿渣水泥”。与我国类似,在乌克兰基辅建筑工程学院发明碱矿渣水泥三四十年后,西方国家才开始较多地研究碱矿渣水泥,并将这种水泥称为“碱激发矿渣水泥”,此名似乎更为贴切。然而作者认为,碱矿渣水泥,顾名思义,就是用碱激发矿渣而得到的水泥,已含有激发之意,不必再加激发二字,科技名词很重要的就是其简洁性,这样使用起来方便。事实上,从古至今的石灰火山灰水泥、现代的石灰矿渣水泥、石灰粉煤灰水泥、石膏矿渣水泥等,

其实质过程都是激发作用,但这些水泥名称中均无激发二字。

矿渣一词含义甚广,广义的矿渣包括了所有的工业生产过程及居民生活中燃料燃烧过程所产生的灰渣。狭义的矿渣则指高炉炼铁过程中产生的矿渣,特别是经水淬或风冷之后的粒化高炉矿渣。这种矿渣活性高、产量大,是所有矿渣中最具有代表性的一种,也是碱矿渣水泥原料中研究最为深入和成熟的一种。本书所论述的碱矿渣水泥与混凝土亦是以粒化高炉矿渣为中心展开的,同时也简述了以其他渣源为原料的碱矿渣水泥与混凝土。此外,还论述了碱-硅酸盐、碱-铝酸盐等碱性胶凝材料。

本书所言之碱是指元素周期表中第 I 族碱金属元素的碱性化合物。

本书所引用的文献有很长的时间跨度,在这一时间跨度里,科技量度单位变化很大。例如,过去强度单位用 kgf/cm^2 ,现在用 MPa ($1\text{kgf}/\text{cm}^2 = 0.0980665\text{MPa}$),过去热量单位用 kcal ,现在用 kJ ($1\text{kcal} = 4.18\text{kJ}$),晶面间距及孔隙尺度过去用 $\text{\AA}$,现在用 nm ($1\text{\AA} = 0.1\text{nm}$)。同样,随着技术的进步,技术标准也在不断改进,20 世纪 50~70 年代,我国水泥用硬炼砂浆来确定水泥标号,如 300、400、500 号等;80 年代改为用水灰比为 0.44 的软炼砂浆确定标号,如 325、425、525 等;而目前则是以水灰比为 0.5 的软炼砂浆确定强度等级,如 32.5、42.5、52.5 等。混凝土的标号过去以 kgf/cm^2 强度单位确定,如 200、300、400 号等,现在则是以 MPa 为单位确定强度等级,如 C30、C40、C50 等。除此之外,各种矿物的化学组成及结构测定也不断精化,各时期的文献也存在差异。为了保持原始资料的风貌,以及方便读者查询,作者在撰写本书时,未作改动。

作为参考,本书附录中列出了原苏联的有关碱矿渣水泥、混凝土和结构的三个技术规程。

作者在碱矿渣水泥与混凝土领域研究的合作者先后有:陈剑雄教授(博士生导师)、甘昌成高级工程师,以及作者的学生吴礼贤教授(博士)、杨长辉教授(博士生导师)、王绍东教授(博士生导师)、徐彬博士、陈友治教授(博士)、刘芳副教授(博士)、嵇亚俊硕士、陈明珠硕士、梁军林硕士、张华硕士、张晓丽硕士、侯灵明硕士、徐清硕士。参加试验工作的有白光工程师、何桂实验师。作者对合作者在研究工作中付出的辛勤劳动和做出的贡献表示高度赞赏,并致以由衷的感谢。王冲副教授(博士)、陈科讲师(博士)对本书的手稿进行了大量计算机输入和加工,完成了本书的电子文稿,作者致以衷心的感谢。

由于作者的水平有限,不足之处恳请读者批评指正。

重庆大学 蒲心诚

2008 年 12 月

Preface

In 1984, in the library of Chongqing Institute of Architecture and Engineering, China, the author found a monograph in Russian called *Alkali Slag Fine Grain Concrete* (Ref. 12). The author was quite excited by reading it and knew that except for common Portland cement and concrete there was another excellent cement and concrete in the world, which had not only quite good hydraulic but also very high strength and excellent durability indexes. Besides, this cement and concrete had technical and economical advantages, such as widespread resource of raw materials, low cost, simple technology of preparation, low investment for manufacture and environment friendly etc. This book deeply attracted the author and introduced him into the research field of the alkali slag cement and concrete. After two and half of years of effort, the author succeeded and had developed an alkali slag concrete with rapid hardening, high strength, low heat hydration, high impermeability, high frost resistance and high corrosion resistance. A large volume of alkali slag concrete elements had been produced in the laboratory of concrete technology at Chongqing Institute of Architecture and Engineering, China. In June, 1987, the Chongqing Science and Technology Commission had organized a technical approval for the "Research Project of Alkali Slag Concrete". Soon after, applications for research projects to National Natural Sciences Foundation of China, Ministry of Construction and National Bureau of Building materials have been accepted in order to continue this study and to solve the problem of too short setting time of Alkali Slag Cement and concrete with the silicate sodium as main component. In August, 1991, the Chongqing Science and Technology Commission had organized a technical approval for the "Research Project of High Grade Alkali Slag Cement". In May, 1998, this Commission had organized another technical approval for the "Research Project of New Generation (neutral sodium salt) Cement". All these achievements of research on alkaline cement have reached the international advanced level of that time.

In 1990, in order to strengthen the international academic exchange and to learn from the inventor of the alkali slag cement, a message was sent to the Glukhovskii of Kiev Institute of Architecture and Engineering, Ukraine, Soviet Union

for inviting him to China to give a lecture. Unfortunately, the professor just passed away and instead, his disciple, Professor Kryvenko answered the message and agreed to visit China. In 1990, Professor Kryvenko came to Chongqing, China on invitation and gave a rich in contents lecture for a week, in addition he presented the author a lot of valuable research works on alkali slag cement and concrete. In October, 1992, the author paid a return visit to Kiev Institute of Architecture and Engineering, Ukraine, and exchanged the author's achievements in this field. Then Professor Kryvenko visited Chongqing twice.

This monograph is based on the achievements of the author and his collaborators, as well as the information of the literature from former Soviet Union and the Commonwealth of Independent States, European countries and U. S. A.

The alkali slag cement was invented in 1957, initially it was called as "soil cement" and the concrete prepared from it called as "soil silicate". In 70s of twenty century it was renamed as "Alkali Slag Cement". Like China, the western countries paid more attention to the study on Alkali Slag Cement only thirty or forty years later after the invention of Alkali Slag Cement by Kiev Institute of Architecture and Engineering, Ukraine and the western scholars called such cement as "alkali activated slag cement" seemingly that such term was more suitable. However, the author of this monograph suggests that the alkali slag cement by its name means that the cement is obtained through activation of slag by alkali, so the word "activated" is unnecessary, the simplicity is quite important for the scientific term and easy for its use. In fact, from the ancient time to now, the lime pozzolanic cement, modern lime slag cement, lime fly ash cement, gypsum slag cement etc during the process of their hardening, the activation always plays its essential role and in these terms no "activated" appears.

The term "slag" has a wide implication. The slag in its wide meaning includes all ash and slag from burning of fuel for industrial manufacture and inhabitants. In narrow meaning, the slag means the product from manufacture of iron in blastfurnace, in particular the blastfurnace slag after water quenching or air cooling. This slag is representative among all slags due to its high activity and large volume of output and as raw material for alkali slag cement, which is the deeply studied. The alkali slag cement and concrete described in this book is based on blastfurnace slag, there are also alkali slag cement and concretes based on other slags. In addition, the basic binding material such as alkali-clinker and alkali-aluminate are introduced as well in this book.

Alkali given in this book implies the basic compound of alkali metals in the first group of periodic table of elements.

The literature cited in this book has a long time span. During this span of time there was great change in units of measure for science. For example, in the past, the strength was expressed in kgf/cm^2 , now it is the MPa ($1\text{kgf}/\text{cm}^2 = 0.0980665\text{MPa}$); formerly, the unit for heat was kilocalorie, now it is the kilojoule ($1\text{kcal} = 4.18\text{kJ}$), $\text{\AA}$ was taken for the planar spacing of crystal and dimension for pores but at present it is nm ($1\text{\AA} = 0.1\text{nm}$). Similarly, with the progress of science and technology, the technical standards were also improved. In the 50-70s of twenty century, in China the grade of cement was determined by earth-dry mortar strength test, such as grade 300, 400 or 500 etc, in 80s the cement grade was determined by plastic mortar strength test with water cement ratio of mortar 0.44, such as 325, 425 or 525 etc, at present, the cement grade is obtained by plastic mortar test with water cement ratio of 0.5, such as 32.5, 42.5 or 52.5. The grade of concrete was expressed in kgf/cm^2 in the past, such as the grade 200, 300 or 400 and now the grade is given in unit of MPa, for example, C30, C40 or C50 etc. Besides, the determination of chemical composition and structure of minerals becomes more precisely, there are also differences in information from literatures at different times. To keep the features and view of original information and for convenient inquiry to the readers, in this book these information have not been updated.

As reference in the appendix three technical specifications about the alkali slag cement and concrete of former Soviet Union are given.

The collaborators of the author in the research of alkali slag cement and concrete are: professor Chen Jianxiong, senior engineer Gan Changcheng, and the students of the author: professor Wu Lixian (Ph. D), professor Yang Changhui, professor Wang Shaodong, Xu Bin (Ph. D), professor Chen Youzhi (Ph. D), associate professor Liu Fang (Ph. D), Ji Yajun (MS), Chen Mingzhu (MS), Liang Junlin (MS), Zhang Hua (MS), Zhang Xiaoli (MS), Hou Linming (MS), Xu Qing (MS). Participated in the experimental work are also engineer Bai Guang, experimentalist He Gui. The author highly appreciates the hard works of collaborators of the author as well as the achievements and contributions devoted by them. Associate professor Wang Chong (Ph. D) and lecturer Chen Ke (Ph. D) had done a large volume of work in manuscript input and processing on computer and accomplished the electronic files of the manuscript, the author expresses

heartfelt gratitude to them.

Due to the limit of author's knowledge, suggestion and discussion are welcome about deficiency in this book.

Chongqing University Pu Xincheng

Dec. 2008

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第 1 章 绪 论

1.1 混凝土的过去、现在和未来

人类使用混凝土做建筑材料已有数千年的历史,最初作为混凝土的胶凝材料的是黏土、石膏、石灰、石灰-火山灰、水硬性石灰。例如,距今已有 6000 多年的西安半坡遗址,其许多围墙就是用黏土混凝土建造的;距今 5500 年前建成的古埃及金字塔采用了石膏砂浆做胶结材;公元前 220 年我国古代劳动人民在修筑世界著名的万里长城时,就曾使用过以石灰做胶结材,拌入砂、黏土配制的石灰混凝土^[1],古希腊、古罗马也曾大量使用过石灰混凝土。至今,石膏、石灰还是广泛使用的胶凝材料,用它们做成的混凝土及制品亦常有应用。但是这些材料的抗水性很差,其应用范围受到限制。

为了改善混凝土的抗水性,古罗马人和古希腊人在石灰中掺入了火山灰,并和砂、石混合成混凝土,这种混凝土的强度比纯石灰的高,而且能在水中逐渐硬化。古罗马人使用的火山灰产于意大利南部波佐利(Pozzuoli),所以称之为 Pozzolana。古罗马人用这种天然的火山灰和石灰做胶结材料配制的混凝土建造了许多著名的宏伟建筑,虽然经过了 2000 多年流水、雨雪、海风的作用,至今仍保存完整,这说明了古代石灰火山灰混凝土具有优良的耐久性。石灰火山灰混凝土的缺点是硬化速率缓慢,强度也较低,而且要受到资源(火山灰)分布的限制。

中世纪之后,罗马帝国衰落,建筑技术与胶凝材料的生产有所衰退。以后,由于资本主义的兴起,工业、交通业和军事建筑等需要高强度的混凝土材料,于是在 18 世纪前后,人们发现了水硬性石灰和罗马水泥,它们都由含有一定数量的黏土杂质的石灰石煅烧而成。这些胶凝材料能在水中硬化,具有抗水性。但是含黏土的石灰石的产地并不多,黏土的含量^①也大不一致,难以广泛和大规模地进行生产。因而,促使人们用人工配料方法制造水泥。以到达大量生产出质量更高的胶凝材料和混凝土的目的。

1824 年硅酸盐水泥(国外称波特兰水泥)的发明(发明者,英国人 Aspdin)正是这样的创造,这一创造揭开了水泥混凝土科学的新纪元,使得混凝土这种人造石在

① 本书在无特殊说明时,所指物质含量均为质量分数。

人类进步中大放异彩。

与石灰火山质水泥和其他胶凝材料相比,硅酸盐水泥的显著优点有:①硬化速率快,具有优良的水硬性和抗水性;②强度增高;③生产受资源限制小。因此,它一问世,就得到了迅速发展。其后 180 余年来,其性能不断提高,品种不断增加,产量不断扩大,所取得的成就大大超过了过去数千年的成就,使得这种水泥混凝土成为现代建筑材料的主体,成为人类用量最大的人造材料。迄今为止,水泥的品种达 100 余种,2006 年仅我国的水泥产量即达 12.35 亿 t。

近 30 年来,由于广泛引入被称为混凝土第五组分的各种外加剂,使得现代混凝土的品种超过了水泥的品种,性能更加提高,并适应于各式各样的使用要求和施工条件。使得混凝土构成一个庞大的家族,成为支撑现代世界文明主要的物质基础。

但是,现代科学与技术的革命,迫切需要混凝土技术在现有成就的基础上取得更加长足的进步。例如,在海洋深处建造结构物,在海面上建造巨大的海上平台,在城市里建设垂直城市,建造高耸入云的电视塔,建造跨越大江、大河、峡谷、海峡的大跨度桥梁,建造现代化高速火车栈桥,建造各种大型的地下建筑以及巨型水坝等。所有这些新奇建筑和巨型工程,都对混凝土材料提出了各式各样的更高要求。但是,其中主要是对混凝土强度和耐久性的要求,未来的混凝土将主要向着提高强度和高耐久性两个方面发展。

钢筋混凝土结构的主要缺点是自重很大,提高强度是降低结构自重的有效途径。当混凝土强度达到 100MPa 时,预应力钢筋混凝土结构的质量^①可以达到和钢结构一样轻,因为此时两者的比强度(强度与质量之比)相等。

目前 C50~C70 的混凝土,已成为通常使用的混凝土,在许多情况下,已使用 C80~C100 的混凝土。在特殊场合下,将使用 C100~C200 的混凝土,甚至强度更高的混凝土。目前,超高层建筑的高度已增至 828m(阿联酋迪拜塔),超大跨桥梁的跨度已超过 1000m(我国苏通大桥 1088m)。事实上美国西雅图的 Two Union Square 大厦的柱子,设计强度就采用 56d 龄期达 135MPa 的硅灰混凝土。我国目前应用混凝土的平均强度还较低(C20~C25),因此,更应加倍努力。

为了大幅度提高混凝土的强度,基于纯硅酸盐水泥是不行的,因为硅酸盐水泥的强度潜力在极大程度上已经耗尽。近 30 年来,许多研究工作者在此方向的苦苦探索并未能使硅酸盐水泥的标号有很大幅度提高,目前硅酸盐水泥的最高标号为 725,但生产中多为 425、525(GB 175—92)。所以研究工作者不得不另寻出路,例如,出现了聚合物浸渍混凝土、聚合物水泥混凝土、聚合物混凝土等新型有机胶结材混凝土和有机无机复合胶结材混凝土。但是这些类型的混凝土价格昂贵,施工

① 旧称为重量,全书同。