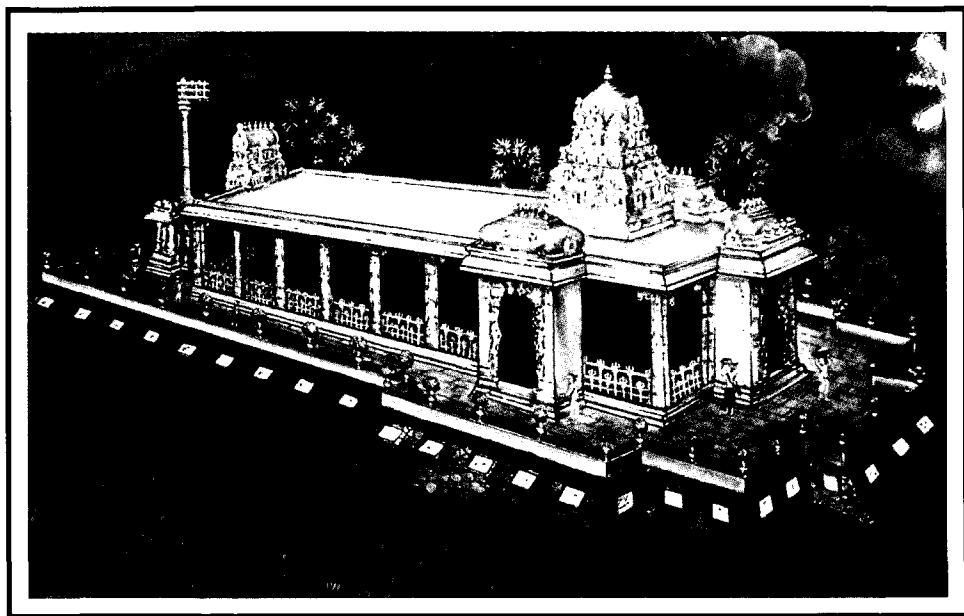


2001

THIRD CANMET/ACI TROISIÈME CANMET/ACI

INTERNATIONAL • SYMPOSIUM • INTERNATIONAL



**SUSTAINABLE
DEVELOPMENT OF
CEMENT AND CONCRETE**

**DÉVELOPPEMENT
DURABLE DU CIMENT ET
DU BÉTON**

EDITOR • V. M. MALHOTRA • RÉDACTEUR EN CHEF



Documents

Document Sharing Hub

Front cover photo: An architectural rendering of San Marga Iraiban Temple in Kauai in the Hawaiian Islands, U.S.A. The temple will be built on a raft foundation of non-reinforced concrete containing 55 percent ASTM Class F fly ash.

Photo courtesy of: Wilbert S. Langley, W. S. Langley Concrete and Materials Technology, Inc., Sackville, Nova Scotia, Canada.



Documents

Document Sharing Hub

Third CANMET/ACI International Symposium on Sustainable Development of Cement and Concrete

Sponsored by
Committee for the Organization of
CANMET/ACI International Conferences
(ACI Council)
Ottawa, Canada

International Centre for Sustainable Development
of Cement and Concrete
(ICON/CANMET)
Natural Resources Canada
Ottawa, Canada

American Concrete Institute
Farmington Hills, Michigan, U.S.A.

Institute for Research in Construction
National Research Council
Ottawa, Canada

Editor
V. M. Malhotra



DISCUSSION of individual papers in this symposium may be submitted in accordance with general requirements of the ACI Publication Policy to ACI headquarters at the address given below. Closing date for submission of discussion is December, 2001. All discussion approved by the Technical Activities Committee along with closing remarks by the authors will be published in the March/April 2002 issue of either ACI Structural Journal or ACI Materials Journal depending on the subject emphasis of the individual paper.

The Institute is not responsible for the statements or opinions expressed in its publications. Institute publications are not able to, nor intended to, supplant individual training, responsibility, or judgment of the user, or the supplier, of the information presented.

The papers in this volume have been reviewed under Institute publication procedures by individuals expert in the subject areas of the papers.

Copyright © 2001
AMERICAN CONCRETE INSTITUTE
P.O. Box 9094
Farmington Hills, Michigan 48333-9094

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by any electronic or mechanical device, printed or written or oral, or recording for sound or visual reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietors.

Printed in the United States of America

Editorial production: Bonnie L. Gold

Library of Congress catalog card number: 2001092471
ISBN: 0-87031-041-0

PREFACE

The ACI Council for the Organization of CANMET/ACI International Conferences on Concrete Technology in association with International Centre for Sustainable Development of Cement and Concrete (ICON), Natural Resources Canada, and Institute for Research in Construction/National Research Council, Canada, is pleased to sponsor the Third CANMET/ACI International Symposium on Sustainable Development of Cement and Concrete in San Francisco, U.S.A., September 16-19, 2001. The first two symposia in this series were held in Ottawa, Canada, October 21-23, 1998, and Hyderabad, India, February 9-11, 1999.

For this symposium more than 100 papers from 20 countries were received, and peer reviewed in accordance with the policies of the American Concrete Institute; 29 were accepted for publication. The accepted papers deal with all aspects of concrete technology and sustainability with the majority of them dealing with the role of supplementary cementing materials in reducing CO₂ emissions.

In addition to the papers that have been published in the referenced proceedings, more than 30 other papers were presented at the symposium. A number of these were published as supplementary papers in a separate volume, and the authors of these papers are encouraged to publish these in technical journals of their choice.

It is hoped that this symposium has brought to the attention of the civil engineering community the high CO₂ emissions released into the environment in the manufacturing of portland cement, and the potential of reducing these emissions by increasing the use of supplementary cementing materials such as fly ash, granulated blast-furnace slag, and rice-husk ash. The technologies are now available that, when used properly, can replace up to 60% of portland cement by these supplementary cementing materials in concrete, while maintaining or enhancing most of the mechanical and durability properties of the concrete produced. With world-wide availability of fly ash > 600 million tonnes per year, the civil engineering community is well placed to use this resource to enhance considerably the supply of cementing materials without expanding the portland-cement-clinker capacity. This will not only help in reducing the CO₂ emissions but will also help in resolving to a great extent the fly ash disposal problem.

Thanks are extended to more than 10 members of the review panel that met in Acapulco, Mexico, in December 2000 to review the papers for this symposium. Without the dedicated efforts of the reviewers, it would not have been possible to have the proceedings ready for distribution at the symposium. The co-operation of the authors in accepting reviewers' suggestions and revising their manuscript is greatly appreciated.

The help and assistance of A. Bilodeau (Chairman), B. Fournier, and R. Chevrier (members) of the slide review panel are gratefully acknowledged. Thanks are extended to H. S. Wilson, M. Venturino, and G. D. Brearley for their help in processing the manuscripts. The contributions of the ACI staff are also recognized.

V. M. Malhotra, P.Eng.

Editor,

Chairman, Third CANMET/ACI International Symposium on Sustainable
Development of Cement and Concrete

September 16-19, 2001

International Organizing Committee
Third CANMET/ACI International Symposium
on
Sustainable Development of Cement and Concrete
San Francisco, U.S.A.
September 16 - 19, 2001

Chairman
Mohan Malhotra
CANMET
Ottawa, ON

Secretary-Treasurer
Harry Wilson
Consultant
Ottawa, ON

Members

Theodore (Ted) Bremner
University of New Brunswick
Fredericton, NB

Noel Mailvaganam
Institute for Research
in Constructions/NRC
Ottawa, ON

Wilbert (Wib) Langley
W.S. Langley Concrete & Materials
Technology Inc.
Sackville, NS

Nelu Spiratos
Handy Chemicals Ltd.
Candiac, Quebec

Contents

Preface

Factor Ten Emission Reductions: The Key to Sustainable Development and Economic Prosperity for the Cement and Concrete Industry by R. Horton.....	1
German Cement Industry's Voluntary Efforts on the Issue of Climate Change — A Success Story by V. Hoenig and M. Schneider.....	15
Non-Ferrous Slag as Cementitious Material and Fine Aggregate for Concrete by S. Monosi, P. Giretti, G. Moriconi, O. Favoni, and M. Colleparidi.....	33
Steel Slags in Cement-Making—The Current Status of Development by A. K. Chatterjee	45
Reducing CO ₂ Emission into the Atmosphere—Achievements and Experience of Croatian Cement Industry by K. Popović.....	73
Performance of High-Grade Concrete with Full Substitution of Aggregates by Recycled Concrete by U. Meinhold, G. Mellmann, and M. Maultzsch.....	85
New Zealand Pozzolans — An Ancient Answer to a Modern Dilemma by W. South and I. Hinczak	97
Use of Thermally Converted Paper Residue as a Building Material by J. Péra, J. Ambroise, J. Biermann, and N. Voogt.....	111
Performance-Based Hydraulic Cements of the New Millennium by S. L. Sarkar and J.-C. Roumain.....	125
Potential of Crushed Waste Calcined-Clay Brick as a Partial Replacement for Portland Cement by R. D. Toledo Filho, B. B. Americano, E. M. R. Fairbairn, J. S. Rolim, and J. F. Filho	147
Feasibility and Performance of Recycled Aggregate in Concrete Containing Fly Ash for Sustainable Buildings by V. Corinaldesi, F. Tittarelli, L. Coppola, and G. Moriconi.....	161

Repercussions on Concrete Permeability Due to Recycled Concrete Aggregate by J. M. Gómez, L. Agulló, and E. Vázquez	181
Use of Recycled Concrete as Aggregates for the Construction of Fish Reefs by T. Yen, K. H. Chen, and Y. W. Liu	197
The Stabilization of Aqueous Heavy Metal Species Using Recycled Concrete Fines by N. J. Coleman, D. C. Johnson, O. L. Shtepenko, and C. D. Hills.....	207
Circulating Fluidized Bed Combustion Ashes as an Activator of Ground Vitriified Blast Furnace Slag by I. M. A. K. Salain, P. Clastres, J. M. Bursi, and C. Pellissier.....	225
Influence of Different Secondary Raw Materials on the Granulated Blast-Furnace Slag Reaction by W. Brameshuber and P. Schröder	245
Influence of Synthesis Temperature on the Hydration of New Cements from Fly Ash of Municipal Solid Waste Incineration by A. Guerrero, S. Goñi, A. Macías, E. Fernández, and M. P. Lorenzo.....	267
Behavior of Chlorine in Cement Manufactured from Municipal Wastes by K. Kawai, E. Tazawa, S. Tanaka, and S. Yokoyama.....	285
Mechanical Properties and Shrinkage of Concrete Made with Eco-cement by S. Tanaka, H. Tanaka, and S. Yokoyama	299
High Volume Fly Ash RCC for Dams: Freezing and Thawing Durability by S. Jacobsen and O. Lahus.....	315
High Volume Fly Ash RCC for Dams — I: Mixture Optimization and Mechanical Properties by O. Lahus and S. Jacobsen.....	331
Microstructure of Concrete from a Crack-Free Structure Designed to Last a Thousand Years by J. Asselanis and P. K. Mehta.....	349
Gap-Graded Concrete Blended with Rice Husk Ash and Fly Ash by D. D. Bui and P. Stroeven.....	359
A Study of the Penetration of Chloride Ions in Rice-Husk Ash Concrete by A. A. Azevedo, M. L. C. Martins, and D. C. Dal Molin.....	379

Reactivity of Lime Activated Pozzolans
by W. J. McCarter, G. Starrs, and T. M. Chrisp 397

Fly Ash from Fluidized Bed Coal Combustion as Complex Cement
Addition
by W. Roszczynialski, W. Nocún-Wczelik, and M. Gawlicki.....415

Mechanical Properties and Durability of Concrete Made with Portland
Limestone Cement
by E. F. Irassar, V. L. Bonavetti, G. Menéndez, H. Donza, and O. Cabrera.....431

Pre-Industrial Manufacturing Tests on Construction Blocks Composed
of Magnesium Slags
by R. Cabrillac, J. L. Gallias, M. Courtial, and G. Pierson.....451

Performance of Alkali-Activated Slag Concrete
by S. Al-Otaibi, C. J. Lynsdale, and J. H. Sharp.....467

Factor Ten Emission Reductions: The Key to Sustainable Development and Economic Prosperity for the Cement and Concrete Industry

by R. Horton

Synopsis: Sustainable development in the concrete and cement industry is achievable in the near future. This paper proposes the viability of a factor 10 reduction in the negative environmental effects of current cement/concrete production through the use of cement blends with minimum portland cement and maximum pozzolanic loading. Such cement blends substantially extend the longevity of concrete and avoid the enormous cost of several repair and replacement cycles. The transition to sustainable concrete technology will be driven not by environmental imperative but rather by market forces pursuing economic advantage through more durable concrete. Market driven economics already in place will soon prove that concrete durability is worth a high premium but is available at a bargain. There is enormous leverage in improving concrete quality as a doubling of the price of highest quality cement would add only 2% to overall construction project costs while the extended service life of the structure would offer a many-fold return on the additional investment. In coming years, the consideration of CO₂ emissions regulations and increasingly valuable internationally traded CO₂ credits will assume an economic importance equal to or greater than capital and operating costs among cement producers. Those who do not move to sustainable concrete technologies will run the risk of losing substantial market share or business failure.

Keywords: CO₂ credits; cement; concrete; durability; economics; emissions; factor 10; pozzolan; rice husk ash (RHA); strength; sustainable development

2 Horton

Robert Horton is CEO and Chairman of Alchemix Corporation, an ash utilization and beneficiation company focused on cement additives, with subsidiaries RHA Technologies, H₂ Technologies Corporation and Pittsburgh Mineral and Environmental Technologies. Mr. Horton has served as executive management in the development of energy and environmental technologies for over 20 years.

INTRODUCTION

At a conference held in Beijing, China in 1996, world experts on the environment and environmental technologies discussed various challenges facing the country and an impressive array of options to address them. After three days of deliberation, the Chinese official in charge of the conference gave his concluding remarks beginning with acknowledgement that a great many good ideas had been presented that should be implemented and, taken together, would make a measurable impact on the environment in China and in the world. Unfortunately, he said, most would not be implemented because they represented cost rather than profit and, in a developing country like China, capital resources would almost always be allocated first to projects with potential to rapidly develop the economy. He told the conference attendees that if they hoped to see their ideas implemented, they must be sold based on economic, rather than environmental benefits. Specifically, he suggested that the only way to sell environmental solutions in China was to be able to say and prove to a potential user, 'I have a secret way to save you money.'

The point made is generally true, not only in China, and embodies a central theme of this paper. To make any industry greener, the case must first be made that the environmentally friendly solution will be more economically profitable. This premise most certainly holds true for the cement/concrete industry. It is entirely within our reach, however, to make vast environmental improvements hand in hand with healthy profits. In fact, this paper outlines a factor 10 improvement in the amount of environmental disturbance created by the production and use of cement (1). Put simply, we have it within our power to arrest environmental degradation due to cement to one-tenth of the current level. The factor ten reduction can and will be achieved. Competitive market forces will drive positive environmental changes because we have the knowledge right now to make concrete formulations based on high-pozzolan content cements that are cleaner, greener, more durable and longer lasting. Not only do such formulations currently exist, they have been tested, proven and advanced over several years in technical papers by researchers in concrete technology, namely, Mehta, Malhotra and others (2, 3).

The futurist Buckminster Fuller theorized that it took 25 years for a systemic change to be integrated into common use (4). Even when the idea is recognized by experts, a period of time is required to overcome the inertia of the marketplace and to make the necessary investments and marketing and operational changes. We have reached such a threshold. For more than two decades those on the cutting edge of concrete technology have touted the rich benefits of pozzolanic cement additives. The drawbacks of pozzolans have been largely overcome and the lines of resistance to their use are now crumbling. The transition to these more durable, environmentally sustainable concretes is underway. It will be made profitably by market leaders while those committed to conventional or environmentally insensitive practices will be left behind.

THE CHALLENGE

Before going further, it is important to take stock of our present situation and forecasts for the future. Current projections estimate world population increasing from today's six billion to nine billion by 2050 and to eleven billion by the end of the century. Providing basic requirements for a population nearly double that of today will intensely magnify pressure for food, water, land, resources, energy, goods and services. As humans struggle to survive, so too the life support system will struggle to endure.

Of course, to imply that humans aspire simply to survive is misleading. What most human beings, in fact, aspire to is not survival but rather aspiration for a better life. Moving toward the prosperity such as that enjoyed by many citizens of developed countries -- home ownership, luxury automobiles, expansive entertainment and media, access to excellent health care, travel, the freedom of wealth -- this is the stuff of the human dream. With the profusion of worldwide information, even the poorest villager in the most remote settlement is aware of the stark contrast of lifestyle available to him or her compared to citizens of more prosperous countries. Unfortunately, accelerating waste-producing consumption is the rule in both developed and developing nations.

In a world increasingly influenced by free markets and more democratic political systems, rising expectations in the developing world must be addressed by government actions that produce visible and tangible improvement quickly, else those populations will support the rise of other leaders promising faster growth. In short, the developing world must and will develop.

In this relentless upward push, the environment will be stressed for resources to make it happen. Even at current levels of human activity, virtually every expert observer agrees on the long-term lack of sustainability inherent in our present use of energy and resources, and the attendant degradation of air, water, soil and climate. Already we are depleting, without adequately restoring,

4 Horton

the natural resources such as fish, forests, arable land, fresh water and clean oxygen-rich air at a rate and in ways that will diminish the quality of all life, including that of the most affluent human beings. In virtually all of the major cities of the world, air available to both the most and least fortunate is equally lacking in oxygen and contaminated with particulate and toxic gases. Increased occurrence of extreme weather events, such as super tornadoes, floods, typhoons and hurricanes, which most experts link to global climate change, devastate rich and poor alike.

Worldwide, environmental degradation is well recognized and, particularly in richer nations, governmental regulations as well as voluntary measures are increasingly enacted to minimize the negative environmental impact of our lifestyles. Unfortunately, many such programs are poorly conceived and have minimum effect. An exception has been the recycling of aluminum in the U.S. Even with the success of this recycling program, however, American consumers and industry still throw away enough to rebuild the country's entire commercial airfleet every three months (5). While everyone wants a clean environment for themselves and their families, those who have not first met basic needs cannot be expected to take the time and effort to be environmentally responsible unless that responsibility carries with it a near term economic reward. In less developed countries, environmental policy must be shown to make money if it is to succeed.

Herein lies the challenge: the reconciliation of societal aspirations with the planet's ability to support them. Meeting this challenge is at the heart of the concept of sustainable development. This central goal of sustainable development is one of the supreme imperatives of our time. It requires significant advances in basic knowledge, in the social capacity and technologies to implement what we know and in the political will to aggressively support sustainable development wherever and whenever possible.

However, even if intentions are the best, laws are passed and the population is educated, history has taught us that environmental-friendly enterprises will not be sustained just because they have long-term planetary benefit. Sustainable development, if it has any hope of realization, will be achieved only if those who must support it will also realize current economic gain for their efforts.

Proceeding from this premise, let us examine the situation in the cement and concrete industry. Concrete is the most widely used building material in the world using more than 1.4 billion tonnes of cement in 1999. The production of portland cement is one of the most energy-intensive and polluting of any industrial processes. Eight percent of all CO₂ released into the atmosphere due to human activity is directly associated with portland cement production (6). Suffice to say that our industry is not yet a poster candidate for sustainable development, but the situation is changing.

WINDS OF CHANGE

The production, distribution and application of cement and concrete is so decentralized and varied that it is difficult to say much that is generally true about participants in the industry except we all want to make more money. While many view the cement and concrete industries as mature and inflexible, powerful winds of change affecting the fundamental economics of our businesses are gathering strength. Those who pay attention to which way these winds are blowing can prosper; those who do not will certainly lose market share, if they survive at all.

Like the rest of the world, managers within the cement and concrete industry will embrace the changes necessary for sustainable development only to the extent that compelling and immediate economic forces drive their actions. Many of these market forces are now in place. At the core of the new realities of the marketplace are two principal economic drivers: 1) a market demand for more durable concrete, and 2) environmental costs and benefits that are beginning to figure as importantly, if not more so, to our bottom line as capital and operating costs.

First, let us look at the economics of durability and why the market embraces it now and will increasingly do so in the future. More and more, the cement and concrete market is dominated by governmental agencies that participate in regulating and/or financing applications of these products. In the United States, 45% of direct cement purchases are for public works. In more controlled economies, such as China, the percentage is much higher. Historically, while regulations and standards existed as local guidelines, frequently they were either poorly conceived and/or not strictly enforced. Into the present, inconsistent products and application techniques lead to many structural failures that are both costly and embarrassing. Even good quality products applied as prescribed have a poor history of durability, causing government agencies, as the ultimate consumers, to themselves become sophisticated and intolerant of poor cement and concrete performance.

Examine, for example, a 1997 National Research Council study in the U.S. that stated its objectives "were to look beyond near-term developments in concrete technology to identify R&D opportunities in innovative, nonconventional materials and processes that have the potential to accelerate the construction process, improve the durability of highway pavement and bridges, and enhance the serviceability and longevity of new construction under adverse conditions. Meeting even one of these three objectives could save billions of dollars in construction and maintenance costs. The U.S. Department of Transportation estimates that the cost of maintaining 1993 highway conditions is

\$49.7 billion per year and the cost of improving them is \$65.1 billion per year. For bridges, the cost to maintain 1994 conditions is estimated at \$5.1 billion per year and the cost of improving them at \$8.9 billion per year.” (7)

For multibillion-dollar reasons like these, a trend toward more stringent durability requirements is well underway. Caltrans (the transportation authority for the State of California) now requires at least 25% fly ash by mass of the cementing materials in concrete products to avert durability problems stemming from alkali-reactive aggregates. The Port Authority of New York and New Jersey has specified a 1000 coulombs charge in the standard ASTM test for rapid chloride penetration (ASTM C1202) to control the permeability of concrete. These are but two of many examples across the United States. The world today increasingly demands specific steps be taken by the concrete construction industry to improve the longevity of its products.

Simple economics is the reason that the trend toward durability requirements will continue. The cost of concrete in most projects is no more than 4% of total project cost. Cement cost is roughly half this amount. If a more reliable or long-lasting structure or road can be ensured by even a doubling of the cost of cement, insurance of durability and quality can be had for a 2% increase in the project cost. To illustrate, take for example a 30-year project at a cost of \$10 million. If the useful life of this project is extended by ten years, giving it a 40-year life, its productive use is extended by one-third, thus saving a building cost of \$3.33 million. If the cement cost in this project were 100% more, or \$400,000 instead of \$200,000, the savings from using a longer lasting formulation would produce a seventeen-fold return.

With savings this compelling, and as projects are increasingly subjected to computer-driven cost modeling, the institutions that set the rules and pay the bills will increasingly insist on maximum durability for many projects, regardless of the price of cement. Economics will drive this decision. Today, the formulations, standards and understanding of what constitutes value in concrete are available instantly and at no cost via email to any interested party.

And there are some very interested parties. The enormous financial strain on the construction budgets of many governmental agencies has reached crisis proportion due to the premature maintenance costs and alarming failure rates of buildings and infrastructure. For this reason alone, the argument for requiring and using the highest-quality, longest lasting cements available is irresistible for all but the most temporary structures. High performance cement is a multi-billion dollar opportunity for our industry and an economic bargain for our customers.

Whereas portland cement and its various types have been the standard for the construction industry for 150 years, new blended cements priced on a performance basis will dominate in the 21st century. This domination will take



hold as the market becomes increasingly educated and willing to pay for performance. Top performance will require far more careful attention to mixing, sizing, water content, aggregates and curing methods than are now commonly practiced by many in the ready-mixed concrete industry. Those who adapt to a higher standard of performance will flourish as products are increasingly customized and priced based on a specific application. The use of blended cements and precasting of concrete will also increase as many advantages of controlling formulation conditions are better understood.

Some people will argue that developing countries in particular will opt to pay less for cement and lower the initial cost of projects. This situation will not persist because of the low incremental cost of higher quality and increased durability of concrete. Self-preservation is well understood by decision makers around the globe. They gain considerable political mileage from a new project or road but little credit for maintenance spending. More durable and longer-lasting projects mean fewer repairs and more money for new projects. Ultimately, officials at the multinational funding agencies will insist on better quality concrete if their funds are to be committed to a given project.

The cement and concrete industry already has extensive knowledge about making better quality concrete, at a price. A great deal can be accomplished toward achieving greater durability by simply teaching concrete buyers that more durable, additive-compatible cements are a bargain even at higher prices. To the extent that the market increasingly shifts to performance-oriented products valued on their strength and durability, prices for superior cements will rise to accommodate incremental cost of achieving superior results. Higher-value, longer-lasting formulations and products will ultimately dominate the market and allow the technology leaders providing them to substantially widen their margins.

Turning our attention to the second major economic driver pushing the transition of our industry toward sustainable development -- the market impact of environmental costs and benefits -- consider first the impact of environmental issues directly on the capital and operating costs associated with our industry. There are many recognized environmental costs already associated with the conventional production and distribution of cement and concrete. Items such as the time and permitting involved in siting a cement kiln are directly affected by the resistance of many localities to have dirty industry locate in their neighborhood. Siting issues can affect proximity to markets and raw materials as well as the ability to install cement production capacity on a timely basis. More than 25 million tonnes of foreign cement was imported into the United States at prices often above local production costs in 2000 due in part to the uncertainties of creating additional kiln capacity. The cost of cement production is also increasing as regulations around the world demand that cleaner, higher cost fuel be used in kilns.

8 Horton

Furthermore, whereas new kilns used to produce portland cement require capital investment of \$150 to \$175 per annual tonne to site and build, pozzolanic materials, on the other hand, often require little or no plant since they are frequently recycled from other industries. Roughly 400 million tonnes of fly ash are produced annually from coal-fired utility boilers worldwide and several billion more tonnes are stored in ponds and piles. For a fraction of the current cost of producing portland cement, fly ash can be recovered and beneficiated to remove carbon and increase its reactivity.

The two most populous nations on earth, China and India, primarily burn coal to generate electricity. They will likely have the largest growth in cement/concrete demand in this century. They have an enormous economic opportunity to use their abundant fly ash resources effectively, both to avoid the cost of disposal and to extend the value purchased with their construction budgets.

Today in the U.S., the typical cement formulation, if it contains fly ash at all, contains 15% to 20% ash by weight of the total cementitious material. Soon the number will typically be 50% to 60% ash. The line will blur when we speak of 'additives' whether the reference is to pozzolan or portland cement.

Percentage fly ash will escalate because:

- improved technology will allow for higher early strength and consistent reactivity of high percentage pozzolan mixtures;
- fly ash will be widely acknowledged for improving critical performance characteristics, such as workability, impermeability and durability;
- industries emitting high levels of CO₂ will pay a penalty for these emissions; and
- whoever can prove emission reductions will earn CO₂ credits.

CO₂ credits will be a major economic factor that will drive the cement industry toward a factor ten environmental improvement. The Kyoto Accords call for the trading of greenhouse gas (GHG) credits, which, of course, includes CO₂ credits (8). Under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), industrialized countries have adopted legally binding emission levels – at 5.2% below 1990 levels on average. These reductions must be made by the first compliance period, 2008-2012.

CO₂ credits will be monetized and traded in much the same manner of the highly successful allowance trading system in the United States to phase out lead in gasoline and cut emissions of SO₂. Cement producers will be taxed on excess emissions. Those using pozzolans in their cements will earn credits to

offset these penalties. Within ten years, CO₂ credits and the way they are managed within the cement industry are likely to be as important as the actual cost of portland cement production.

Credits are earned by those who take actions that reduce the amount of CO₂ produced by a given activity. For example, replacement of 25% of portland cement by fly ash in blended cement will reduce the CO₂ required in production by 250 kilograms, or 25%. Therefore a 250-kilogram CO₂ credit would be available for each tonne of blended cement produced with a 25% ash component. On the other hand, companies that produce high levels of CO₂ will be liable to either reduce their emissions to acceptable levels or enter the CO₂ market to buy credits sufficient to reduce their net emissions to regulatory levels.

In order to create a viable market, verification of benefits must be established as well as motivated buyers and sellers. A host of major companies and countries are addressing these issues today. Natsource, a leading broker of energy products, points out that the cost savings in the lead and SO₂ programs in the U.S. have been substantial, amounting to as much as 50% when compared with a control policy in which no trades were allowed. Trading policies have sharpened market awareness and yielded a competitive advantage. They have also spurred development of emission reducing technologies (9).

The likelihood of CO₂ emission reduction regulation poses a significant financial risk to emitters. Emitters must therefore cost-effectively manage their risks in order to protect revenue flow and shareholder value. An emitter might wait to see exactly what reductions are required before purchasing the required credits in the CO₂ market, but projected future prices of greenhouse gas emissions suggest that the cost of compliance at these levels could be crippling to the emitter.

In the current GHG market, banked credits and forward streams of emission reduction credits are trading at attractive prices. Therefore, many emitters are hedging exposure on a forward basis right now. The CO₂ market offers the most cost-effective route to achieving future emissions reduction compliance levels and is driving the market on risk management concerns rather than current compliance issues. In effect, the CO₂ market offers a cost-effective insurance policy that the international market is increasingly pursuing.

From an economic viewpoint, cement companies that do nothing to substantially offset the CO₂ effect from production and use of their products will be forced to add a new cost of production. Today, a one-tonne CO₂ credit is worth between \$1.50 and \$4.00. Most experts agree that its market value will increase because it offers a feasible economic means to create net environmental gains while operating highly polluting but profitable industries. While it is impossible to say precisely what price credits will command, predictions range from \$25-\$100 per tonne for credits in the intermediate term.

A useful analog to this situation is found in the coal industry. Historically, coal sold at prices roughly 30% below oil and natural gas on an energy equivalent basis because it was solid, harder to transport and store, dirtier and more costly to burn. Nonetheless, when the price of oil and gas rose, the price of coal rose, like a shadow, a similar percentage amount.

In November 1991, revisions to the Clean Air Act were enacted that called for SO₂ credit trading. Further action has imposed stringent restrictions on NO_x emissions and the trading of their credits. Additional data are also being reviewed relative to heavy metal emissions and these gases are likely to be tightly restricted as well. Because coal, and not oil and gas, emit these gases, the cost of removing them, i.e., the environmental cost of burning coal, has become a real economic penalty. Coal now sells, on an energy equivalent basis, for roughly \$1 per million Btu – less than 20% of the current price of equivalent energy in natural gas.

There is no question that, in the near future, the price of cement will also more nearly reflect the environmental costs associated with its production and use. Because cement, like coal, is a relatively environmentally unfriendly commodity, the incremental cost will be substantial. It should also be noted that, like coal, regulations and credits will eventually factor nearly all environmental costs in order to prevent the exporting of pollution to less developed and regulated economies. For example, cement imported from Thailand to the United States will be subject to environmental penalties associated with its production as well as its transportation. In this case, any labor materials or regulatory savings for polluting in Thailand rather than the U.S. will be defeated by higher transportation costs and environmental penalties.

It is a central tenet of sustainable development that, wherever possible, transportation of commodities should be minimized. In this regard, it is interesting to note that roughly 10% of all oil traded worldwide is consumed in its transportation and that more than 25 million tonnes of cement are imported into the U.S. alone. Most international trade in cement will cease to make economic sense when all environmental costs for cement are factored, especially when those costs include incremental penalties associated with extraordinary transportation and its incremental requirement of fossil fuel combustion.

WHAT CAN BE DONE?

Generally, methods available to cement makers to measurably reduce CO₂ emissions involve the replacement of portland cement with fly ash or other pozzolanic material and/or the improvement of cement characteristics enabling less cement to be used for a specific purpose.

A cement company adding 25% fly ash and earning a 25% credit per tonne produced could reduce its CO₂ penalty and production costs between \$6.25 (at \$25/tonne) and \$25 (at \$100/tonne) per tonne. Further savings will be realized as the actual cost of portland cement production, due to environmental costs to site and operate kilns, is expected to increase everywhere.

Therefore, substitutions of pozzolanic material for portland cement is a way of avoiding high capital costs and environmental penalties associated with new kilns while meeting incremental demand for cement. Also, when pozzolanic material is locally available, its use in place of portland cement can reduce the substantial environmental and transportation costs associated with the fuels burned to transport cement internationally.

For years up to this point, several barriers have existed to the use of pozzolans in cement. Fly ash, in particular, has borne the stigma of being a waste product. The most significant resistance to its use involved inconsistencies in the ash due to variability of coals burned at generating plants. When low NO_x burners were introduced in these plants, fly ash carbon content rose to levels that can sometimes conflict with other cement additives. But the most important barrier has been longer set times and slower strength gain compared to portland cement. New technology and cement formulations now exist that overcome these drawbacks. Carbon reduction technology is available from several sources and new beneficiation technology is capable of producing consistently small-particle, highly reactive fly ash.

The potential to replace portland cement with pozzolanic material other than fly ash is also viable. In Singapore, SsangYong Cement routinely formulates excellent blended cements containing 70% blast-furnace slag. Worldwide, silica fume and metakaolin are both sometimes used to replace 10% of portland cement. A newcomer to the pozzolan market, rice hull ash, which, in future years, will be widely available in Asia and to a more limited extent in other continents, promises tremendous advantages for concrete high early strength plus durability approaching that of Roman concretes.

For the foreseeable future, there is plenty of pozzolanic material to replace 50% or more of all cement used worldwide. Not all of it is currently captured and available for use as cement replacement, but approximately 400 million tonnes per year of fly ash is produced from coal-fired utility boilers alone and additional billions of tonnes have been impounded over the last 75 years.

GETTING TO A FACTOR TEN REDUCTION

If the average life of concrete today is 30 years and if it were possible to increase that to 180 years, five cycles of repair and replacement would be eliminated and emissions would be reduced by a factor of five. If the cement used was a 50/50 blend of pozzolan and portland cement, original emissions would be halved and the reduction factor would double to 10.

The net reductions are actually much larger since premature failures and replacements of concrete entail substantial associated activities and waste such as mining, transportation, planning, human resources and production capacity to support it. Perhaps the greatest waste is the incalculable waste of time, fuel and inactivity that, for example, the resurfacing of a bridge, street or freeway causes as traffic snarls.

Making cement stronger so that a smaller amount is needed for the same job can make further, calculable emission reductions. If, for example, an 8% cement-to-concrete ratio provides sufficient strength to a concrete foundation where 12% is commonly used, a reduction of 33% could be achieved.

Clearly, highly durable concrete is possible. One must only point to the Pantheon in Rome or the 2000-year-old aqueduct still functioning in Segovia, Spain to find evidence of vastly more durable concretes. Today, evidence of highly improved concretes exists as well. Mehta and Langley, for example, recently oversaw the installation of a temple foundation in Hawaii, which, due to absence of cracking and very low permeability, is expected to endure a thousand years (10). After one year, the 57% fly ash cement foundation did not show even a single hairline crack.

A variety of characteristics of modern concrete must be addressed in order to substantially increase its longevity. These include:

- reduced heat of hydration;
- reduced porosity;
- limited free water;
- acceptable early strength; and
- high durability.

High loadings of 40% to 60% fly ash with portland cement go a long way toward achieving these goals. If properly formulated and applied, fly ash will provide substantially increased durability as well as a reduction in the amount of CO₂ emitted. An array of superplasticizers, to reduce water, silica fume or rice

husk ash to reduce porosity and increase durability might be used to obtain even more exceptional durability and early strength than high percentage fly ash cements alone. Obviously, if CO₂ credits are effective, and stronger, longer-lasting cements are achieved, a substantial premium allowing wider profit margins will exist for those who replace part of portland cement with pozzolans.

CONCLUSIONS

Moving into the 21st century, the cement and concrete industry has an opportunity to accomplish extraordinary goals. It can simultaneously champion sustainable development and make ten-fold improvements in the amount of environmental disturbance created by its products while increasing profitability. The industry needs only realize that such goals are entirely within reach and achievable through concrete formulations based on tested and proven high-pozzolan content cements that are cleaner, greener, more durable and longer lasting. Educated demand for high durability, environmentally friendly concretes exists today and will continue to grow. Those who rise to the occasion of sustainable development in this industry will prosper, those who do not will most likely not survive. The cement and concrete industry has built the modern world. It must now meet the challenge to preserve the environmental integrity of the planet as we forge the structures of this new century.

-
- (1) Hawken, P., Lovins, A, and Lovins, L.H., *Natural Capitalism*, Little, Brown and Company, Boston, 1999.
 - (2) Mehta, P.K., "Concrete Technology at the Cross Roads," ACI SP-144, 1994.
 - (3) Malhotra, V.M., "Properties of High-Volume Fly Ash Concrete," *Advances in Concrete Technology*, CANMET, 1992.
 - (4) Fuller, B., *Critical Path*, St. Martin's Press, New York, 1981, p. 148.
 - (5) <http://www.epa.gov/epaoswer/non-hw/muncpl/factbook/internet>
 - (6) "Cement and Concrete: Environmental Considerations," *Environmental Business News*, Vol. 2, No. 2, March/April 1993.
 - (7) National Materials Advisory Board Committee on Nonconventional Concrete Technologies for Renewal of the Highway Infrastructure, *Nonconventional Concrete Technologies: Renewal of the Highway Infrastructure*, National Academy Press, Washington, D.C., 1997.
 - (8) Kyoto Protocol, Framework Convention on Climate Change, Dec. 1997.

14 Horton

- (9) <http://www.natsource.com/environmental/ghg/background.html>
- (10) Mehta, P.K. and Langley, W.S., "Monolith Foundation: Built to Last a 1000 Years," Concrete International, July 2000, pp. 27-32.

German Cement Industry's Voluntary Efforts on the Issue of Climate Change— A Success Story

by V. Hoenig and M. Schneider

Synopsis: In 1995 the German cement industry committed itself to a 20 % reduction in its specific fuel energy consumption between 1987 and 2005. In 2000, this commitment has been adapted to the international agreements, particularly to the Kyoto Protocol. Now the voluntary agreement includes a reduction of the specific energy-related CO₂ emissions from 1990 to 2008/12 by 28 %. As the burning and grinding facilities have been widely optimized during the past years, the German cement industry is planning to increase the substitution of fossil fuels by waste fuels and to promote the marketing of blended cements.

From 1987 to 1999 the German cement industry's efforts have led to a reduction of the energy related CO₂ emissions by 3,6 million tonnes per year. The share of waste fuels has been increased from 4 to 23 % and the clinker portion in cement has been decreased from 86 to 80.6 % by using more granulated blast-furnace slag and unburned limestone as the main constituents in cement.

To what extent other instrument like emission trading, joint implementation or clean development mechanism can be used in the future to achieve further reductions, will depend on mutual arrangements and implementation by the international community.

Keywords: CO₂ emissions; cement; clinker; Kyoto Protocol

Dr.-Ing. V. Hoenig is head of the Environment and Plant Technology Department of the Research Institute of the German Cement Industry. Beneath research activities in the field of environmental technologies and energy efficiency, he is deeply involved in the organization of the German Cement Industry's voluntary agreement on climate change.

Dr. rer. nat. M. Schneider has been working in the field of environmental research and politics related to the cement production for many years. Now he is Chief Executive of the Verein Deutscher Zementwerke and Head of the Research Institute of the German Cement Industry.

1 Introduction

The World Commission on Environment and Development describes "sustainable development" as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". That is why the German cement industry has taken its part of the responsibility for a sustainable construction economy. Cement and concrete are two of the most important construction materials. In the context of sustainable development it is necessary to consider the whole life cycle of cement including its production processes, its use in concrete and finally the disposal or recycling of concrete structures at the end of useful life. One of the most important aspects of sustainable development is the protection of the world climate. Climate change is a global problem, which is caused by the emission of so called "green house gases" of all sectors of the society, industry as well as house heating and traffic.

The production of cement affects the climate by its CO₂ emissions originating from the burning process, from raw materials, and indirectly from electric power consumption. In 1995 the German cement industry decided to contribute to the abatement of CO₂ emissions by committing itself to reduce its specific fuel energy consumption in 2005 by 20 % compared to 1987. At a constant production rate this would lead to a CO₂ reduction of about four million tonnes per year.

The German cement industry is characterized by a mixture of small family owned companies with one production plant, medium sized companies with 2 to 4 plants on national level and a few multinational operating companies. In 2000, 38 companies in total have been producing cement in 64 plants, 42 of them producing clinker and cement. The geological sites are spread all over Germany (**Fig. 1**). About 50 % of the cement production capacity is concentrated in the regions of Westfalia, Baden-Württemberg and Bavaria. In 1999, cement production amounted to some 37 million, including exports of 2,5 million tonnes. Cement imports of nearly four million tonnes are mainly from Eastern neighbours such as Poland, Czechia and Slovakia.

In 1999, the total turnover amounted to 5.5 billion DM (approximately 2,5 billion U.S. dollars). The number of direct employees was 11,300. Most of the cement companies are members of the technical and scientific organisation, the Verein Deutscher Zementwerke (VDZ), and of the market orientated Bundesverband der Deutschen Zementindustrie (BDZ).

2 Voluntary Agreement on Climate Change

The commitment is part of the "umbrella agreement" of the German industry, organised by the Federation of German Industries (BDI). In this "Declaration on Global Warming Prevention" 17 industry associations agreed to take concrete measures in order to reduce specific CO₂ emissions by 20 % by the year 2005, compared to 1990. Since then another 2 umbrella associations have joined this agreement. As a result almost 80 % of industrial final energy consumption and more than 99 % of public power generation are now covered by the agreement. As a service in return, the German Government confirmed to abstain from introducing additional legal or fiscal measures like CO₂ or energy taxes for the participating industrial sectors.

In 1996, a transparent and verified reporting concept was jointly drawn up in order to provide politicians and general public with detailed and credible information on advances made by all individual sectors. An important part of the monitoring system is an external verification of the process by a neutral institution, the Rheinisch-Westfalian Institute for Economic Research.

As a reaction to the political developments on national and international level, particularly the signing of the Kyoto Protocol in 1997, in the year 2000 the German industry extended its voluntary agreement and adapted it to the international arrangements. In order to support the German government's aim to reach its 21 % reduction target by 2012, the industry increased its target to 28 % by 2005 and a 35 % reduction of specific green house gas emissions by 2012. At the same time, the German cement industry revised its target to a 28 % reduction of its specific energy related CO₂ emissions between 1990 and 2012, including fossil fuels and electric power. Taking into consideration the CO₂ emissions from raw materials, the total specific CO₂ emission of the German cement industry will be reduced by 16 % until 2012.

The main instruments for the implementation of the cement industry's voluntary agreement are:

- improvement of the manufacturing processes
- increase in the substitution of fossil fuels by waste fuels
- changing of the cement composition (increasing of the production of blended cements)
- research and development in the fields of process technology, use of secondary materials, properties and application of blended cements
- know-how transfer (education of plant staff, exchange of experiences on engineering and management level)

3 Improvement of Manufacturing Processes

In the cement production process fuel energy consumption is mainly used for the burning of the cement clinker. As the clinker burning process is one of the most energy intensive industrial processes high energy costs have forced the cement industry for decades to increase the energy efficiency of their processes. As a consequence the specific fuel energy consumption of the German cement industry has been reduced by more than 50 % during the last 50 years (**Fig. 2**). Therefore, today the energy efficiency of the total process amounts to more than 70 %. This high efficiency is the result of a continuous optimization process, that has taken place independently from energy cost, but following the investment cycles of a capital intensive industry.

Electric energy is mainly used for the preparation of raw material (about 35 %), for burning and cooling of the clinker (about 22 %), and for cement grinding (about 38 %). As it can be seen from **Fig. 3** the electric energy consumption of the German cement industry has been continuously increasing since the 1950s until the mid 1980s. This increase can be put down to the higher requirements for product quality, that means higher cement fineness and to environmental protection measurements. Meanwhile, this development has been stopped and the specific power consumption of the German cement industry varies between 0.367 and 0.385 GJ/tonne of cement (102-107 kWh/tonne). The reduction during the years after 1990 is partly caused by the optimization of the grinding facilities in the East German plants.

3.1 Installation of New Plants

After the German reunification in 1990, the energy consumption pattern of the cement industry of former East Germany has changed drastically. The specific fuel energy consumption came down from 4250 kJ/kg cement in 1987 to 2905 kJ/kg in 1997 (**Fig. 4**). In year 2000, the measures implemented – representing an investment volume of approximately 2.5 billion DM (1.2 billion U.S. dollars) without enclosure of local capacity – has been completed. After the installation of new kilns in the Schwenk plant in Bernburg and in the Rüdersdorf plant of Readymix as well as the complete modernization of the Deuna plant (Dyckerhoff) and Karsdorf plant (LAFARGE) the local production facilities now belong to the most modern in the world. By this transfer of technology from West to East Germany, it was possible to reduce the energy consumption of the East German cement plants by 35 %.

The reduction potential in West Germany was much smaller. Here the specific energy consumption was reduced from 3130 to 2995 kJ/kg cement in 1997. In West Germany also new kilns have been installed during the past few years. As under German market conditions an increased production is not possible, the installation of new kilns is only economically viable if the capacity of several old kilns can be combined to one big new kiln. Therefore, the new kiln 7 of the Teutonia plant near Hannover with a capacity of 2500 t/d replaced two older kilns of smaller size. In the Lägerdorf plant of the

Holderbank subsidiary ALSEN, a new kiln with a capacity of 4500 t/d went into operation in 1995 and replaced two Lepol kilns. In the Lengerich plant of Dyckerhoff a new kiln with a capacity of 3700 t/d is being installed and shall be put into operation in 2001. This kiln will replace three Lepol kilns with the same total production capacity. During the past few years the structure of the German cement industry's kiln facilities has changed significantly. As can be seen from **Fig. 5** this development has taken place in West Germany over a long time period. Between 1972 and 2000 the share of the dry process technology with low energy consumption increased from 56 to 84 % of the total clinker capacity. The share of grate preheater kilns has been reduced from 30 to 15 %. The last wet kiln was closed down in the 1970s. **Fig. 6** shows, that a similar development has happened in the East German countries, however, in a significantly shorter time period of only 10 years (1990 to 2000). There, more than 90 % of the clinker capacity is covered by the dry process technology.

Today, new kilns are exclusively constructed as dry process kilns with calciner, tertiary air duct and grate cooler. The advantage of this technology is not generally a lower energy consumption, but the smaller dimension of the rotary kiln, which means lower investment. The lower radiation losses of the kiln itself are compensated by higher waste gas losses of the preheater and radiation losses of the calciner. Moreover, by the separate precalcining of the raw meal a smoother kiln operation can be reached, that is an important requirement for a lower energy consumption. As precalciner kilns are mostly constructed with a higher kiln capacity, the increased implementation of this technology has led to an increase in the energy efficiency of the German cement plants.

3.2 Optimization of Existing Kilns

As the investment cycles in the cement industry are very long – counting in decades rather than in years – the burning and grinding facilities are underlying a continuous modernization process. Two examples shall be presented:

1. The Heidelberger plant in Leimen is running two Lepol kilns, which came into operation in 1961 and 1973. As a conversion to the dry process has not been economically viable, the kilns were totally renovated between 1991 and 1994. By the restoration of the LEPOL preheater and the rotary kiln, the adaptation of the clinker cooler to the state of the art technology, the implementation of a modern process control system and the addition of a new electrostatic precipitator the consumption of fuel and electric energy could be reduced by 8, respectively 17 %. Moreover, the environmental situation of the plant has been significantly improved. The kilns are now running with a specific fuel energy consumption of about 3200 kJ/kg clinker and have therefore reached an energy efficiency level, which is at the limit of the technology.
2. In the Dyckerhoff plant in Gölheim the two preheater kilns with a capacity of 1200 and 1800 t/d went into operation in 1963 and 1965, respectively. In 1997 the raw meal preheaters of both kilns

were modernized. Using a new immersion tube technology the pressure drop of cyclone stages could be reduced by 40 - 50 % at the same separation efficiency. This led to a reduction of the required fan power and hence the electric power consumption. In 1998 both kilns were equipped with a modern kiln control system, that led to a saving of fuel energy of about 100 kJ/kg of clinker.

3.3 Waste Heat Recovery

Besides radiation energy losses of cement kilns are – depending on cooler technology – the cooler waste air, the kiln waste gas, and in some cases the bypass gas. Most of this energy is usually utilized for the drying of the raw material and coal and in some cases for the drying of other cement constituents, like blast-furnace slag.

In the former times, many cement kilns in Germany were equipped with waste heat boilers for the use of the waste gas energy. During the last 20 years many experiments have been carried out to find practical solutions for the utilization of the remaining energy losses of modern cement kilns. Experience shows that the specific investment and operation costs are very high and possible efficiency levels are low.

The production of electricity is only sensible under specific circumstances, because the efficiency of waste heat boilers running at 350° C is very low. Nevertheless, two waste heat recovery projects have been implemented in the German cement industry during the past few years.

The Rohrbach plant in the South of Germany is operating a precalciner kiln with a capacity of 1 600 t/d. This plant is located close to the only German oil shale deposit. In a fluidized bed power plant a part of the oil shale is burned and electricity is produced. The burned oil shale has very good pozzolanic and hydraulic properties and is used as a main constituent of the produced cement. Moreover, a part of the oil shale is used as fuel in the calciner and at the same time the burned shale is used as raw material component.

As power generation facilities have been already available, a waste heat boiler was installed in the middle of the 5 stage preheater in 1996. The existing preheater cyclones have been replaced by new cyclones with a low pressure drop. By the implementation of the boiler, the temperature after preheater decreased from 350 °C to 235°C. Produced steam is used in the existing power plant for the production of 2.1 MW electric power. The produced power comes up to 30 kWh/t of clinker and covers about one third of the power consumption of the cement plant.

In the Heidelberger plant in Lengfurt the cement kiln with a capacity of 3150 t/d has been equipped with an ORC facility (**O**rganic **R**ankine **C**ycle) for the use of the clinker cooler waste air. As the humidity of the raw material in Lengfurt is rather low, the calorific content of the cooler waste air could not be used for drying processes. As the tem-

perature of the waste air is below 275 °C the implementation of a normal steam and power generation process for a waste heat utilization was not feasible, because of low efficiency. The ORC process is a technology, which is at the time being, mainly used for the power generation from geothermal sources. In this process, the turbine is operated with an organic solvent instead of water. Using the whole waste air volume of 150,000 m³/h at a temperature up to 275 °C an electric power production of 1.13 MW could be achieved, that covers about 12 % of the power consumption of the plant.

3.4 Reduction of Electric Power Consumption

Electric power consumption amounts to some 10 % of the total energy consumption of a cement plant. The share of electricity costs however is about 50 % of the total energy costs. Reduction measures are predominantly aiming at a higher energy efficiency of the raw material and the cement grinding processes. However, electric power consumption and cement quality are in a close relationship. Efficient grinding systems, like the high pressure grinding roll or the vertical roller mill, have been largely implemented in the German cement industry. Nevertheless, the energy reduction potential cannot completely be used, because the properties of cements from high efficient grinding systems differ significantly from cements ground in conventional ball mills. Main reason is the steeper particle size distribution of the produced cement. Moreover, the energy efficiency of the grinding system using roller mills is related to the grinding pressure. Experiences with these mill types in the past have shown, that high grinding pressures led to significant damages of the rollers. Therefore, the operational pressure had to be reduced in order to achieve sufficient mill operation life.

Besides the mill type, the energy saving that can be achieved, is related to the cement type and the total grinding system. The implementation of a roller press for the pregrinding of cement compounds in a closed circuit grinding device with a ball mill can reach to an energy saving of 7 to 15 %. From the energy point of view, the finish grinding of the cement in a high efficient grinding roll would be the optimum. The energy demand could be reduced by 25 to 50 % compared to a conventional ball mill. But the achieved cement quality as well as unacceptable wear of the rollers are preventing this.

3.5 Remaining Energy Reduction Potentials

Table 1 gives an overview of the energy reduction potentials of different technical measures. The data are related to a conventional kiln or mill without having carried out optimization measures. As the heat recovery from the burned clinker and the clinker cooler has an important influence on the total burning process, the saving potential of the cooler is rather high with 40 to 200 kJ/kg clinker. As the investment in modern cooler technology is usually economically viable, most of the German cement plants have already adapted their clinker coolers to the state of the art.

22 Hoenig and Schneider

On the basis of the energy data of all German cement kilns, the VDZ estimated the maximum reduction potential of the specific fuel energy consumption. Assuming an achievable fuel energy consumption for greenfield plants of 2900 to 3200 kJ/kg clinker – depending on kiln capacity – a maximum reduction of 9 % of the fuel energy consumption could be achieved. The necessary investment would be 2 to 4 billion DM (1 to 2 billion U.S. dollars), and this amounts to some 40 to 80 % of the yearly cash flow of the German cement industry.

4 Promotion of Blended Cement Consumption

4.1 Quality Aspects

Besides the largely completed technological modernization of the kilns and grinding plants, the German cement industry sees further potential for reducing its specific energy consumption by an increased production of blended cements. Generally, the German and European cement standards allow the substitution of the cement clinker by other constituents. In the new European cement standard (EN 197-1) the cement types are divided in five main groups according to their contents of other main constituents besides clinker. In Germany, the important groups are CEM I, CEM II and CEM III. While the cements in the CEM II group may contain 6 to 35 % of other main constituents, CEM III cements may contain from 36 to 80 %. In Germany, only granulated blast-furnace slag from the iron industry and unburned lime stone are of technical importance. For the estimation of this potential, the availability of granulated, blast-furnace slag as well as the different properties and performance of the slag containing cements have to be considered.

Generally, the reactivity of granulated blast-furnace slag (latent hydraulic reaction) differs from the reactivity of cement clinker (hydraulic reaction). Blast-furnace slag hydrates – depending on fineness and composition – slower than cement clinker. Therefore, the performance of slag containing cements has to be recognised in the concrete production. Usually, CEM II cements have comparable properties to Portland cements. CEM III cements with usual fineness and containing large volumes of blast-furnace slag differ from Portland cements mainly by:

1. a slower hydration reaction. Because of the slower hardening reaction they have a lower two-day strength. As the slag hydration continues in the presence of moisture, these cements reach a higher final strength in concrete. Because of the lower reaction at early ages, concrete made from CEM III cements are more sensitive to curing than usual Portland cements.
2. Because of a lower heat of hydration, which is due to the lower clinker portion and to the slower hydration reaction of the slag, CEM III cements are well suited for huge or massive components, like foundations.

Concrete incorporating large amounts of blast-furnace slag that has been well cured has a very dense micro structure. Such concretes are advantageous when a high resistance against chemical attack is required. Furthermore, these cement types have a low effective al-

kali content, which is necessary to avoid damaging reactions between alkalis and concrete aggregates. These influences of granulated blast-furnace slag on some technological properties of the concrete show, that the selection of suitable cements is dependant on the individual area of application and that a simple change of cement types is not possible.

In CEM II cements 1 kg of slag can be substituted for the same quantity of cement clinker. This means, that the thermal energy for this amount of clinker can be saved nearly completely. However, further thermal energy is necessary for the drying of the slag as well as – possibly – for the transportation of the slag to the cement plant. As granulated blast-furnace slag has a lower grindability compared to clinker, slag requires more electrical energy for grinding it to a fineness to the same fineness. Furthermore, cements containing slag have to be ground to a higher fineness to achieve comparable properties than portland cement. This may double the electric power consumption for the cement grinding, depending on the cement type.

Figure 7 shows the relationship between the specific primary energy consumption (related to cement) and the portion of other main constituents in the cement. For example, the production of a CEM II/B-S with a slag content of 35 % requires 29 % less fuel energy, compared to a portland cement. In this calculation, the drying of the slag has been considered. Taking into consideration the electric power consumption for the clinker burning process, the cement grinding and other sources like transportation and storage, the saving is reduced to 21 %. When the portion of other constituents is increased up to 80 % (CEM III/B-S) the saving of fuel energy consumption amounts to some 67 %. The reduction potential related to the total primary energy consumption is however 49 %. As can be seen from Fig. 7 the power consumption related to cement is only lightly influenced by the clinker portion. The electrical savings in the clinker burning process are entirely eliminated by the higher demand for the cement grinding.

4.2 Market Development

In 1996 the German iron industry produced 4.2 million tonnes of granulated blast-furnace slag. The iron industry is planning to increase this amount to 6.1 million tonnes in 2001. Therefore, several new granulating plants have been installed during the past few years. That means, that the availability of total amount of granulated blast furnace slag will increase by some two million tonnes within 5 years. Furthermore, blast-furnace slag is imported into Germany from the neighbour countries.

Granulating devices have been built in joint ventures between the iron and the cement industry. In 1995, the cement industry used 3.6 million tonnes of slag for the cement production. This amount will increase by more than 1.5 million tonnes in 2000, and the same amount of clinker will be substituted. This would lead to a reduction of the energy related CO₂ emissions of about 330000 tonnes per

year. Including the savings of CO₂ emissions that originate from the decarbonation of the limestone, this would correspond to a reduction of 1.1 million tonnes per year.

Traditionally, the market portion of the cements containing slag has been about 20 % of the total German cement consumption. Besides the implementation of the required equipment, the experience shows, that it is necessary for the cement producers to promote the slag or limestone containing cements in the market. Therefore, many cement companies have started promotion campaigns aiming at a continuous change of the consuming habits of the cement consuming industry. Until 1997, the clinker portion in cement was traditionally and continuously in the range of 85 to 86 %. The cement industry's efforts succeeded in decreasing this to 83.5 % in 1998 and 80.6 % in 1999. The delivery of slag containing CEM II cements with slag contents up to 35 % increased from 1.0 million tonnes per year in 1997 to 4.4 million tonnes per year in 1999. At the same time the delivery of portland limestone cement increased from 1.6 to 1.85 million tonnes per year and the CEM III cement containing large amounts of slag increased from 3.9 to 4.6 million tonnes per year.

5 Utilization of Secondary Fuels

Figure 8 shows the development of the fuel consumption derived from energy sources from 1987 to 1999. The graph shows that the amount of secondary fuels has increased from 4 % in 1987 to 23 % in 1999. The secondary fuels have mainly substituted lignite and hard coal. Besides this the use of pet coke has increased significantly from 0.7 to 10 % during the same period. The German cement industry sees a significant contribution to the reduction of green house gas emissions by the utilization of the energy content of waste fuels. These fuels would otherwise have to be land-filled or incinerated, often under worse energy efficiency conditions. By using those secondary fuels in rotary kilns, natural fossil fuels like coal are substituted equivalently related to their energy content and with a total efficiency of more than 70 %. Therefore the cement industry is striving for an acceptance on political level that the use of secondary fuels will be counted as free of CO₂ emissions in a global sense.

This political agreement, which exists in several European countries, can be supported by the results of several life-cycle analyses for different wastes, like plastics, waste oils and waste tyres. **Table 2** gives an overview of the positive contributions of the waste utilization in the cement industry compared to other processes. The table shows that, for example, the use of 1 tonne of plastic waste leads to energy saving of 13.6 GJ/t of plastic, compared to incineration, and a reduction of green house gas emissions of 2330 kg CO₂ equivalents.

6 Green House Gas Emissions

The total CO₂ emissions from the cement production process are estimated on a world wide level to amount to approximately 1 tonne of CO₂ per tonne of cement.

6.1 Energy Related CO₂-Emissions

The formation of carbon dioxide in the clinker burning process occurs when fuel energy is converted to process heat in the kiln. Furthermore, fuel energy is consumed for drying processes for other cement constituents like slag. This specific CO₂ emission coming from fossil fuels has been reduced in the German cement industry from 0.280 tonne CO₂/tonne of cement in 1990 to 0.198 tonne CO₂/tonne in 1999. A change from coal to other fossil fuels with lower specific CO₂ emissions like gas are impossible in Germany because of economic reasons. Besides environmental reasons, the competition forces the cement industry to lower its energy costs by substituting fossil fuels by waste fuels.

The electric power consumption covers only some 10 % of the total energy consumption of the cement plants. As primary energy however, it's portion of the total energy consumption and therefore the CO₂ emissions is not negligible. Basing on the fuel mix of the German power generation industry the power related CO₂ emission of the German cement industry decreased from 0.072 tonne CO₂/tonne of cement in 1990 to 0.068 tonne CO₂/tonne in 1999. In absolute figures the energy related CO₂ emissions of the German cement industry have been reduced by 2.4 million tonnes per year from 1990 to 1999.

6.2 CO₂ Emissions from the Calcination of Limestone

The portion of CO₂ generated from the raw mixture depends on the reception of the raw materials, but the variations are rather low. In Germany it is about 0.53 tonnes of CO₂ per tonne of clinker. **Figure 9** shows the development of the specific CO₂ emissions of the German cement industry from 1990 to 1999. The graph shows that the raw material related CO₂ emissions have decreased only to a small extent from 0.450 to 0.427 tonne CO₂/tonne of cement. This reduction is due to the increased use of slag and limestone in blended cements. Table 3 gives an overview of the CO₂ emissions of the German Cement Industry in the year 1999 divided to the different sources.

6.3 Other Green-House Gases

Besides CO₂ in the Kyoto Protocol five other gases are mentioned as particularly important for the climate change: nitrous oxide, methane, sulfurhexafluoride, hydrofluorocarbons and perfluorocarbons. These gases have a significantly higher green house potential compared to CO₂. Except methane the other mentioned gases are not generated in the cement production process. Nitrous oxide can be generated under certain conditions, if ammonium containing compounds are given to the process for NO_x reduction (SNCR technology). Measurements by the Research Institute of the German cement industry have shown, that the N₂O concentrations in the waste gas of cement kilns are in the range of < 1 to 5 mg/m³, and are therefore, in the range of the detection limit of the analysing method.

Methane is generated from the organic content of the raw materials. In the German cement plants, the emissions of organic compounds range from 10 and 100 mg/m³, with 30 mg/m³ as the average. The

portion of methane is about 50 %. On this basis, an estimation shows that the specific CH_4 emission from cement production is about 30 g/tonne of cement. Recognising the CO_2 equivalent factor of methane of 21 kg CO_2 /kg CH_4 the share of methane of the total green- house gas emissions of the cement industry come only up to about 0.1 %.

7 Conclusions

In 1995 the German cement industry committed itself to a 20 % reduction in it's specific fuel energy consumption between 1987 and 2005. In 2000, this commitment has been adapted to the international agreements, particularly to the Kyoto Protocol. Now the voluntary agreement includes a reduction of the specific energy-related CO_2 emissions from 1990 to 2008/12 by 28 %. As the burning and grinding facilities have been widely optimized during the past years, the German cement industry is planning to increase the substitution of fossil fuels by waste fuels and to promote the marketing of blended cements.

From 1987 to 1999 the German cement industry's efforts have led to a reduction of the energy related CO_2 emissions by 3,6 million tonnes per year. The share of waste fuels has been increased from 4 to 23 % and the clinker portion in cement has been decreased from 86 to 80.6 % by using more granulated blast-furnace slag and unburned limestone as the main constituents in cement.

To what extent other instrument like emission trading, joint implementation or clean development mechanism can be used in the future to achieve further reductions, will depend on mutual arrangements and implementation by the international community.

Table 1: Reduction potentials of the cement production process

measure	thermal energy consumption [kJ/kg clinker]	electric power consumption [kWh/tonne of cement]
I. burning process		
preheater		
• additional cyclone stage	80 - 120	- 0,1
• new cyclone geometry	25 - 75	0,7
kiln		
• low primary air burner	50 - 80	----
• control system	20 - 100	1
• mineralizers	80	- 1
cooler optimization	40 - 200	----
II. grinding processes		
raw material preparation		
• Vertical roller mill instead of ball mill	----	3 - 6
cement grinding		
• control system	----	0 - 3
• high pressure grinding roll in closed circuit process		4 - 10
• high pressure grinding roll in finish grinding process		10 - 25

Table 2: Environmental benefit of secondary fuels in the cement process (related to 1 tonne of waste)

	unit	waste tyres	waste oil	waste plastics
compared process	----	incineration	recycling	incineration
green house gases	kg CO ₂ equivalent	1800	1736	2330
energy consumption	MJ	17000	2587	13600

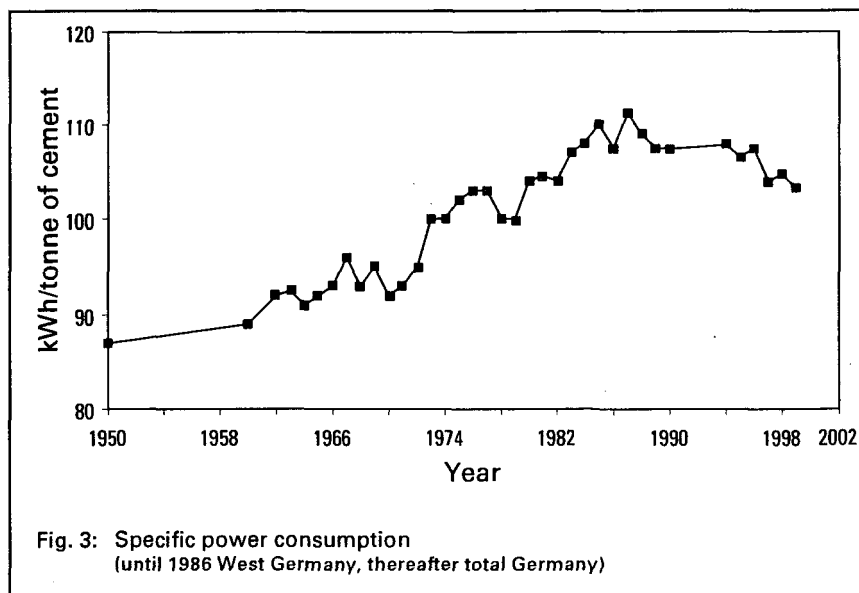
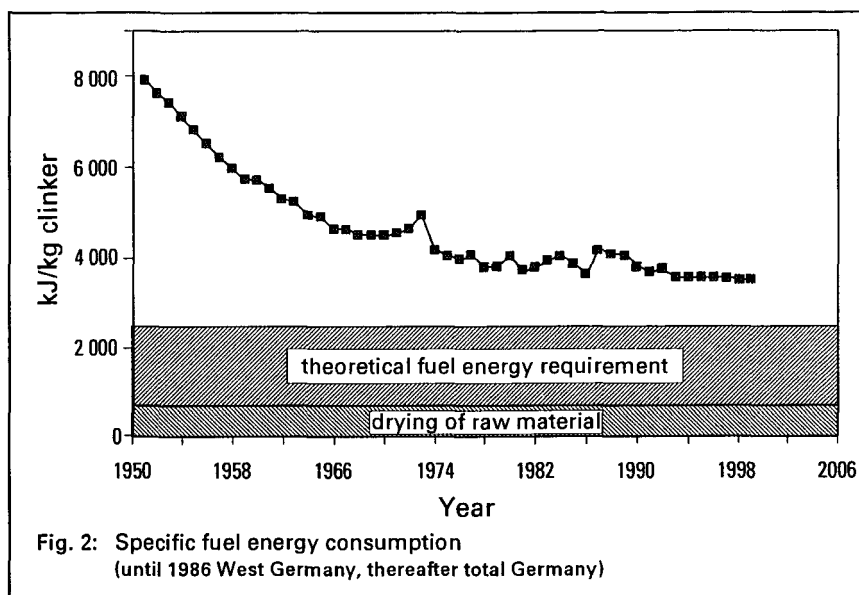
Table 3: CO₂ emissions of the German Cement Industry in the year 1999

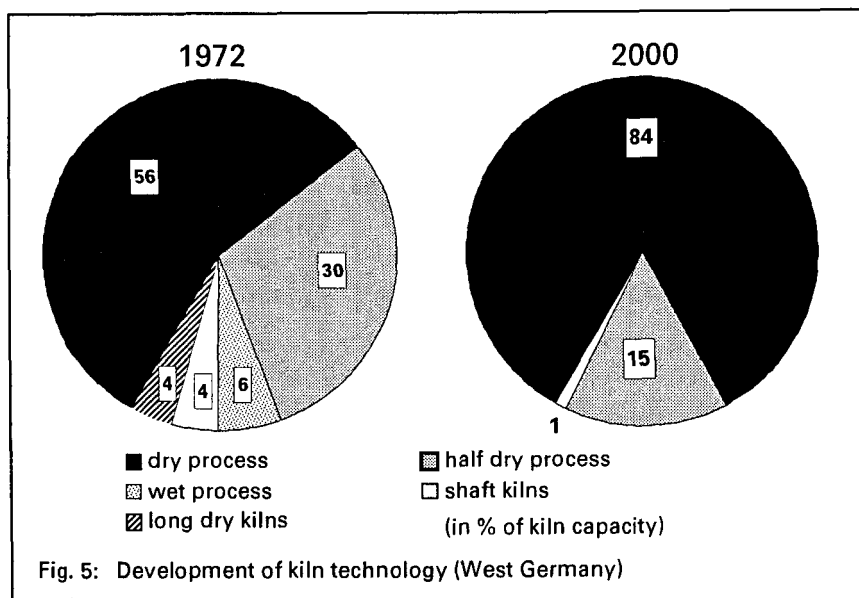
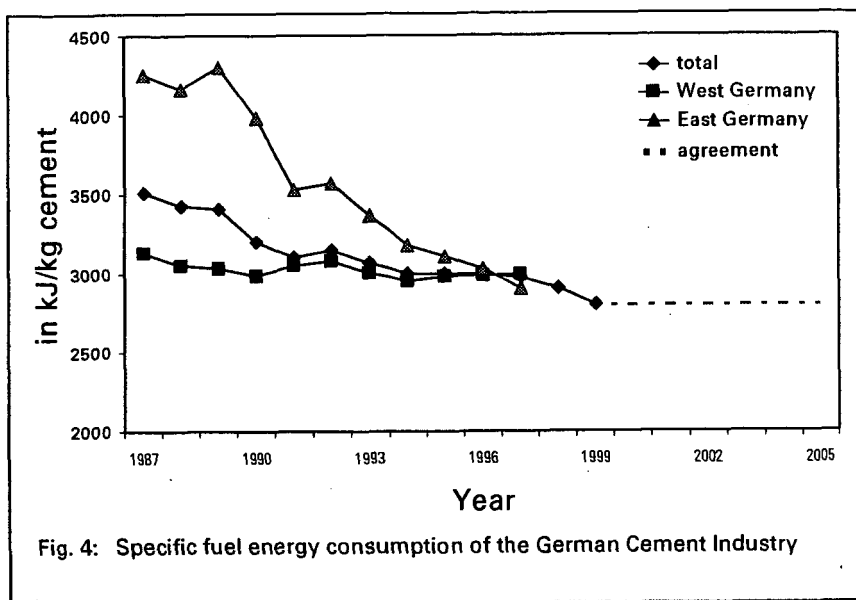
	specific [tonne CO ₂ /tonne cement]	total [10 ⁴ tonne CO ₂ /year]
from fuel consumption ¹⁾	0, 199	7, 26
from electric power consumption	0, 068	2, 50
from calcination of limestone	0, 427	15, 61
total	0, 694	25, 37

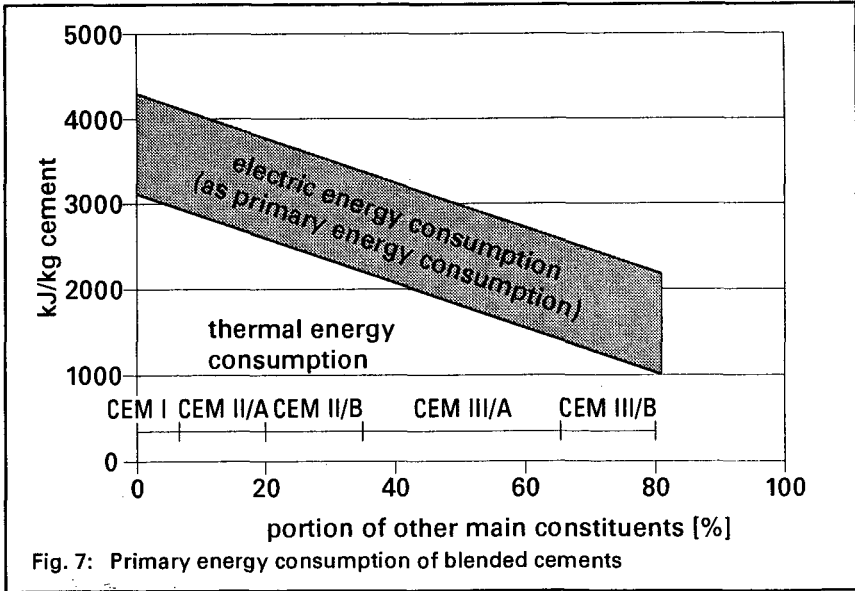
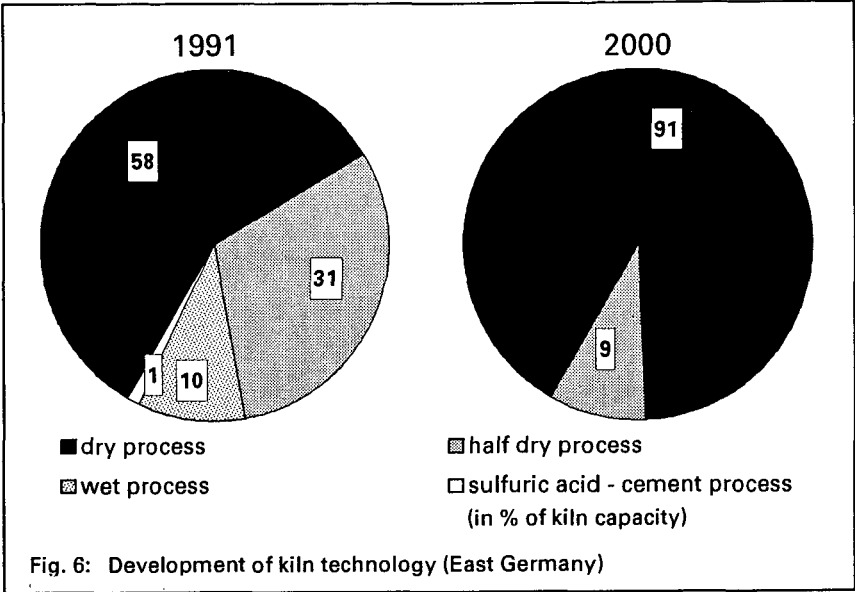
¹⁾ • without secondary fuels

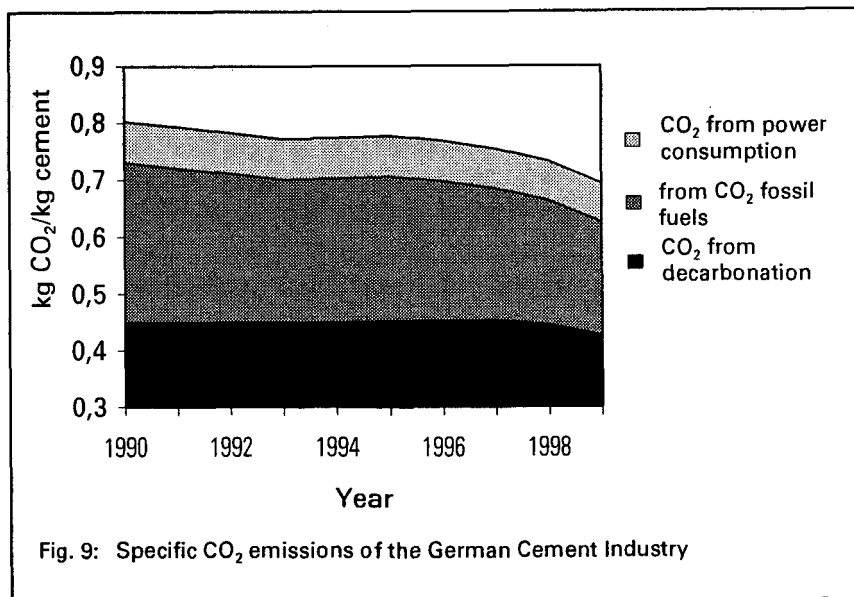
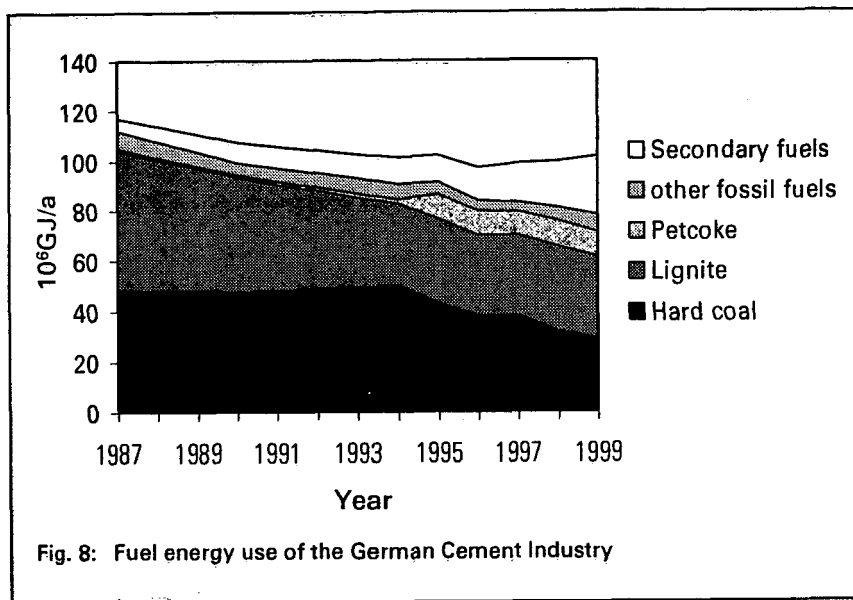


Fig. 1: Production sites of the German Cement Industry









Non-Ferrous Slag as Cementitious Material and Fine Aggregate for Concrete

by **S. Monosi, P. Giretti, G. Moriconi, O. Favoni, and M. Collepardi**

Synopsis: A non-ferrous slag from the production of metallic zinc was studied as a new ingredient for concrete. It was used in two forms: ground and un-ground material. The ground slag replaced 15% of portland cement, whereas the un-ground slag replaced 20% of the natural sand.

Five different concrete mixtures were studied, all with a water-cementitious materials ratio of 0.60:

- reference mixture with portland cement and natural aggregates;
- concrete mixture with ground non-ferrous slag replacing portland cement;
- concrete mixture with un-ground non-ferrous slag replacing sand;
- concrete mixture with ground non-ferrous slag replacing portland cement and un-ground slag replacing sand.

Additionally, for comparative purposes, a ground granulated blast-furnace slag was used to replace 15% portland cement.

The following properties were studied: compressive strength; heat development through change in temperature; and immobilisation of heavy metals of the non-ferrous slag through water-leaching tests.

- The compressive strength development of the concrete with the ground non-ferrous slag was the same as that of the corresponding concrete with ground, granulated blast-furnace slag;
- When un-ground slag was used to replace sand there was a negligible decrease in the early compressive strength;
- When both ground and un-ground non-ferrous slag were used there was a significant retardation in the development of compressive strength during the first 2 days;
- The early heat development was slightly reduced due to the portland cement replacement and the temperature peak was significantly delayed when both ground and un-ground non-ferrous slag were used;
- The leaching by water of heavy metals from the hardened specimens was negligible and then the immobilisation of zinc and lead of the slag into the cement matrix was very effective.

Keywords: cementitious materials; concrete; fine aggregate; non-ferrous slag; portland cement; zinc

Saveria Monosi is Professor of Materials Science and Technology at the University of Ancona, Italy. She is author or co-author of numerous papers in the area of concrete durability and chemical admixtures.

Paola Giretti is a Professional Civil Engineering working in Ancona.

Giacomo Moriconi is Professor of Materials Science and Technology at the University of Ancona, Italy. He is author or co-author of numerous papers in the field of cement chemistry, concrete technology and building materials.

Orlando Favoni is a technician of the Materials Laboratory in the Engineering Faculty of the University of Ancona, Italy.

Mario Collepardi is Professor of Materials Science and Technology at the Politecnico of Milan, Italy. He is author or co-author of numerous papers on concrete technology and cement chemistry. He is also the recipient of several awards for his contributions to the fundamental knowledge of superplasticizers and their use in concrete.

INTRODUCTION

With the beginning of the twenty-first century we are entering in an era of sustainable development, since it will not be possible, in the future, to consider technological aspects only, without giving equal importance to the ecological balance in the planet earth (1).

From this point of view, cement and concrete industries can be considered to be environmentally friendly since a large amount of waste materials, such as fly ash or blast furnace slag, can be advantageously used in manufacturing cementitious products. In other words, the use of fly ash and blast-furnace slag in cement and concrete industries is helpful for both manufacturing cementitious products with improved properties (for instance durability) and for reducing the disposal of waste materials.

However, other waste materials are available, for instance from non-ferrous metallurgical industries, which should be taken into consideration as supplementary cementitious materials. Not necessarily all those waste materials can act as effective additions as fly ash or blast furnace slag do. Nevertheless, these waste materials should be studied in order to assess both their influence on the concrete properties and side effects on the environmental compatibility such as the release of dangerous emissions (2).

The purpose of the present research is to study the possible utilisation of a non-ferrous metallurgical slag from the zinc industry as an ingredient for concrete replacing cement and/or natural sand. This is an other example of reuse of waste material to bring the concrete industry into new era of sustainable development.

EXPERIMENTAL: MATERIALS AND METHODS

Cementitious Materials. Portland cement, granulated blast-furnace slag (GBFS) and non ferrous-slag (ISS) from Imperial Smelting process (metallic zinc industry) were used as cementitious materials. Table 1 shows the chemical analysis of these materials.

Both GBFS and ISS were ground to approximately the same fineness in a laboratory mill so that the percentage of retained material on the 0.180 mm sieve opening was 0.1% for both. Blended cements were manufactured by replacing 15% of portland cement with ground GBFS or ground ISS. Compressive strength of standard mortars according to European Norms (EN 197) with a w/c of 0.50 and sand/cement of 3 are shown in Table 2 and indicate that blended cements are as strong as portland cements at 28 days with lower strength at early curing age (2 days).

Aggregates. Natural sand and gravel were used as aggregates. For some special mixtures un-ground ISS was also used as fine aggregate to replace 20% of natural sand. Figure 1 shows the particle size grading of these three aggregates.

Concrete mixtures. Three concrete mixtures with ISS were studied, all with a water-cementitious material ratio (w/cm) of 0.60:

- a) concrete mixture with ground ISS replacing portland cement (15%);
- b) concrete mixture with un-ground ISS replacing natural sand (20%);
- c) concrete mixture with ground ISS replacing portland cement (15%) and un-ground ISS replacing natural sand (20%).

Moreover, two reference concrete mixtures, again both with a w/cm of 0.60, were produced for comparative purposes:

- d) concrete mixtures with portland cement and natural aggregates;
- e) concrete mixtures with ground GBFS replacing portland cement (15%);

Table 3 shows the composition of the five concretes where the slump level was kept in the range of 220-240mm;

Methods. Concrete specimens were compacted and cured at room temperature. The following properties were measured:

- compressive strength;
- change in temperature due to heat of hydration;
- release of heavy metals (zinc and lead) from ISS through leaching tests.

Compressive strength measurements were carried out on cube specimen (100 mm) cured at 23 °C and R.H. of 95% for a period ranging from 1 to 90 days.

Change in temperature measurements were carried out by a thermocouple into concrete specimens placed at an initial temperature of 23 °C in polystyrene formworks for at least 96 hours.

Release of heavy metals tests were determined by measuring the concentrations of zinc and lead ions in containers where 5 litres of water at 23 °C was kept in contact with each cube concrete specimens (100 mm); than the concentration of Zn and Pb in water was measured by ICP AES (Inductively Coupled Plasma Atomic Emission Spectroscopy).

RESULTS

Figure 2 shows compressive strength as a function of the curing time for the two reference mixtures, with portland cement (CEM I 52.5 R according to EN) and GBFS blended cement (CEM II/A-S 52.5 R according to EN), and for the ISS blended cement (CEM II/A-Q 52.5 R according to EN), all with natural aggregates. There is no difference between the strength of the concretes with the two blended cements with 15% of GBFS or ISS: both are slightly lower than that of the portland cement concrete. For instance, the 28-day compressive strength is 43 Mpa for the portland cement concrete, 38 Mpa for the ISS blended cement concrete and 37 Mpa for the GBFS blended cement mixture.

Figure 3 shows the compressive strength of the portland cement mixture and natural aggregate and that of the two concrete with either portland cement or ISS blended cement both with the un-ground ISS replacing 20% of natural sand. When un-ground ISS replaces the natural sand in the portland cement mixture there is a negligible decrease in the early compressive strength (Fig.3). When ISS is used as both ground cementitious material and natural sand there is a significant decrease in the early strength (no strength at all at 1-2 days) and only a slight strength decrease at later ages (7-90 days). These results can be related to the effect of the ISS slag addition on the hydration rate of portland cement.

Figures 4 and 5 (related to the thermal change caused by the heat development rate) indicate that there is a negligible retardation (in terms of the delay of thermal peak) in the early portland cement hydration when either portland cement is replaced by 15% of ground ISS (Fig.4) or natural sand is replaced by 20% of un-ground ISS (Fig.5). On the other hand, in the presence of both ground and un-ground ISS, the delay of the thermal peak from about 10 hrs to about 42 hrs (Fig.5) indicates that there is a strong retardation in the portland cement hydration. This can explain why at 1-2 days there is no strength in the presence of ISS replacing both 15% of Portland cement and 20% of natural sand (Fig.3).

The retardation, which is much lower when ISS is used to replace either portland cement (Fig.4) or natural sand (Fig.5), can be related to the effect of

heavy metallic ions (such as those available in the ISS waste) on the early portland cement hydration (3).

Leaching tests for zinc and lead ions are shown in Fig 6 and 7, respectively. There is no problem in the release of zinc which is negligible, and lower than the limit of 3 mg/l in the Italian Standard (4), regardless of the use of ISS in replacing cement and/or natural sand (Fig.6).

As far as the lead is concerned, the concentration of the released metal is significantly higher in concrete mixtures containing ISS with respect to the reference mixtures with portland cement or GBFS-cement (Fig.7). However, the lead concentration is significantly lower than the limit of 50 $\mu\text{g/L}$ in the Italian Standard (4). Moreover, the lead release is very low (about 5 $\mu\text{g/L}$ vs. 50 $\mu\text{g/L}$ of the Italian Standard) when ISS is used to replace 15% of portland cement.

CONCLUSIONS

The compressive strength of concrete mixtures with a non ferrous ground slag (from the Imperial Smelting process) replacing 15% of portland cement is slightly lower (38 vs. 43 Mpa at 28 days) than that of the reference mixture. The strength reduction is very close to that of concrete with ground blast-furnace slag replacing 15% Portland cement.

The strength reduction is negligible when the non- ferrous un-ground slag is used to replace 20% of sand. However the combined used of both ground and un-ground slag significantly reduces the early strength (1-2days). This effect is related to the retardation of the portland cement hydration measured through the delay in the thermal peak due to the heat development.

The retardation can be related to the effect of metallic ions, such as those (Zn, Pb, etc) present in the non-ferrous slag, on the portland cement hydration.

There is no substantial problem for the release of Zn and Pb from concretes when the ground non-ferrous slag replaces 15% of portland cement. With the use of both ground and un-ground non-ferrous slag to replace portland cement (15%) and natural sand (20%), the release of Pb is higher (32mg/L) but lower than the limit of 50 mg/L of the Italian Standard.

REFERENCES

- (1) P. K. Mehta "Bringing the Concrete Industry into a New Era of Sustainable Development", Mario Collepardi Symposium on Advances in Concrete Science and Technology, Editor: P.K. Mehta, pp. 49-67, 1997.

- (2) P. Schiessl and I. Hohberg "Environmental Compatibility of Cement-Based Building Materials", Mario Collepardi Symposium on Advances in Concrete Science and Technology, Editor: P.K. Mehta, pp. 27-48, 1997.
- (3) M. Collepardi "Water Reducers/Retarders", Chapter 3, Concrete Admixtures Handbook, Editor: V. S. Ramachandran, Noyes Publications, pp. 116-210.
- (4) Italian law, D.M. 5/2/1998.

Table 1 - Composition of the ISS non-ferrous slag from Imperial Smelting process

Constituents	Percentage
FeO	29.85
CaO	15.37
SiO ₂	14.65
Al ₂ O ₃	5.43
MgO	1.30
K ₂ O	1.11
Na ₂ O	0.86
Zn	4.77
Pb	2.03
C	0.66
Cu	0.55
SO ₄ ²⁻	0.39
MnO	0.43
TiO ₂	0.19
PO ₄ ³⁻	0.18
B	0.08
SrO	0.04
Cl ⁻	0.04

Table 2 - Comprehensive strength of mortars with Portland and blended cements according to the EN/197 European Norms

Cement type (EN/197)	Composition (%)			Compressive Strength (MPa)		Strength class (EN/197)
	Portland	- GBFS	- ISS	2 days	28 days	
CEM I	100	-	-	42	60	52.5R
CEM II / A-S	85	15	-	35	61	52.5R
CEM II / Q-S	85	-	15	32	59	52.5R

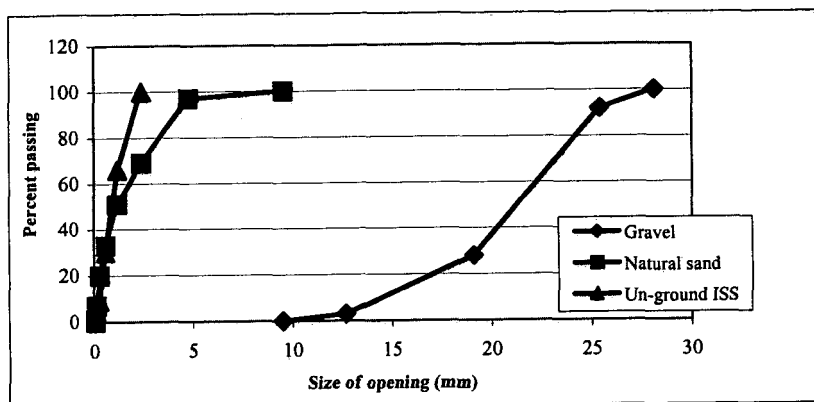


Fig. 1 - Particle size grading of the natural aggregates (sand and gravel) and un-ground ISS.

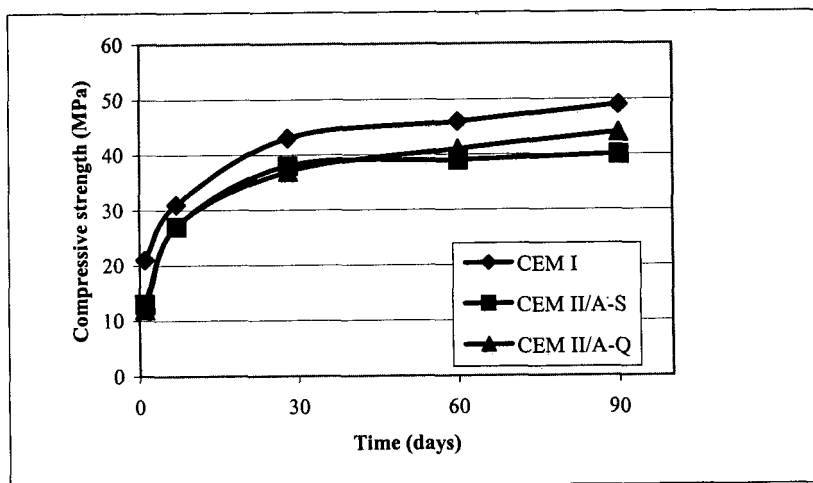


Fig. 2 - Compressive strength of concrete mixtures with CEM I (portland cement), CEM II/A-S (15% ground GBFS) and CEM II/A-Q (15% ground ISS), all with natural aggregates.