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Cement in the 1990s: Challenges and Opportunities [and Discussion]

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Cement in the 1990s: challenges and opportunities

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[Plates 1 and 2]

Despite large gaps in knowledge of cement science, cement and concrete are the preferred materials for much civil engineering construction. As the gaps are filled, cement and concrete should become even more valuable construction materials. The gaps stem in large part from the inability to characterize cements and their hydration products in unambiguous terms.

For many reasons, there have been significant barriers to cement research. The barriers have resulted in fragmentation of research efforts among groups with less than adequate mixtures of skills. Nevertheless, the authors believe there will be a revolution in cement technology based on an integration of research efforts through cooperation on national and international levels. It will be assisted by advances in telecommunications and the application of computers to materials characterization, management of distributed data bases, the development of mathematical models representing the state of the art of cementing reactions, and education of technologists working with cement and concrete. The revolution will require the development of new standard specifications for cements, particularly standards free from unnecessary prescriptive requirements.

The challenge and the opportunity for the 1990s is to make cements and concretes more uniform, more predictable materials than they are at present.

Introduction

Society depends upon cement and concrete for the constructions that represent its largest capital investments. In 1981 the value of buildings and other constructed facilities in the United States was estimated to be $\$5.3 \times 10^{12}$; this represents about 70% of the national wealth (*Statistical Abstracts of the United States* 1981).

Perhaps because of the commodity nature of cement and concrete and their 'low technology' image, investments in cement and concrete research do not appear to be proportional to the importance of these products to society, and the effectiveness of the research activities is lessened by fragmentation. In spite of the weak support for such research, we believe that a revolution in cement technology is coming. In this paper we speculate about the changes in cement technology we expect between now and the end of the century. The revolution we foresee will result from the combined influence of computers and new methods of materials characterization on understanding the factors affecting cement performance.

Because cement and concrete are less well understood than metals such as steel and aluminium, and because they can be more easily tailored to meet special needs than wood, their potential for growth appears high. Since, for the most part, cement and concrete are likely to remain as commodities, the greatest technical need is to be able to predict their performance with a high degree of confidence. Research must, therefore, contribute to uniformity of performance and performance prediction, as well as development of new and improved materials and applications. The required research will necessarily address both cement manufacture and use.

Many of the comments made in this paper apply to concrete as well as cement, even though concrete may not always be mentioned explicitly. We shall discuss needs for scientific and technical research, improved standards, and specialized education for technologists working with cement and concrete. All of these pose challenges and opportunities.

The N.M.A.B. report on the status of cement and concrete research and development in the United States

The 1980 report on the *Status of cement and concrete research and development in the United States* (Roy 1980) began with a disturbing, but undoubtedly true statement, about R. and D. in the cement and concrete industry, 'The health of the industry 20 years from now will reflect strongly the quality and scope of the effort exerted today, but there is little evidence that their relationship is widely recognized'. (The role of new ideas in initiating and sustaining progress is shown schematically in figure 1.) The report concluded that, though research and development in cement and concrete can yield great rewards, spending for basic research on cement and concrete is minimal and it is very limited for all other types of research. Further, collaboration and flow of scientific and technological information among cement producers and users and the related industrial, governmental and academic establishments is inadequate to advance the state of the art. The unsatisfactory levels of research and development in cement and concrete reflect the fragmentation of the industry, the Federal tax structure, the generally low return on investment, and the absence of centres for relevant scientific and technological education.

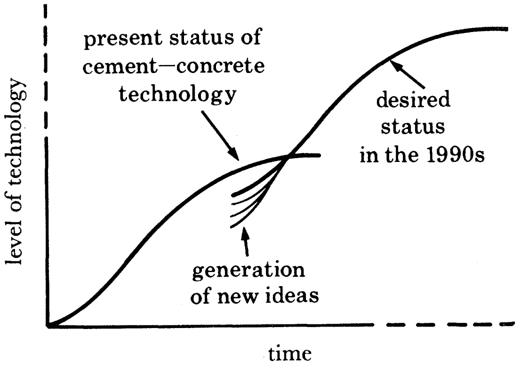

Figure 1. Influence of knowledge transfer on practice. New ideas, some transferred from other fields of materials science, must be reduced to practice to produce a new level of cement and concrete technology.

The report recommended that government agencies with responsibilities for energy, materials, the environment and construction should increase their support of long-range fundamental research on the manufacture and use of cement and concrete, and that special attention should be devoted to studies of (*a*) basic mechanisms, such as hydration and crystal-phase development in cement, and hardening and strength development in concrete; (*b*) long-term behaviour and durability in extreme environments; (*c*) use of energy and resources in producing cement and of utilizing concrete products; (*d*) the interaction of experiment, theory, and modelling.

A thought-provoking table indicating areas for needed improvement of concrete, table 1, was included in the report. The table draws attention to the range of uses to which cement and concrete are put; the range of properties that may have to be considered in selecting cement and concrete for a specific application; and the fact that, in various applications, cement and concrete compete with clay brick, adobe, steel, plastic, timber, aluminium and asphalt.

The challenge to the cement industry in the 1990s is to produce materials that, when used in concrete or other products, have high cost-effectiveness as compared to competitive materials. That this can be done seems evident since cement and concrete are already the materials chosen for much civil engineering construction, despite the many gaps in knowledge about factors affecting their performance. As the gaps are closed, the performance of cement and concrete in traditional and potential new uses should improve substantially.

To help the reader understand our views of the opportunities and challenges for cement in the 1990s, we shall speculate about cement (and concrete) technology as it may be 10 or 15 years from now.

Speculations about cement technology in the 1990s

Considering the changes taking place as a result of developments in computing and techniques for materials characterization, we believe the cement technology of the mid-1990s will have the following features.

(*a*) The generally accepted knowledge of the performance of cements and concretes will be stored in computer data bases and in computer-based mathematical models.

(*b*) Computer-based expert systems (Stefik *et al.* 1982) analogous to those used in medical diagnostics (Shortliffe 1976) will be available to aid designers and specifiers of concrete and other materials, thereby making the latest and best information quickly and easily available to all.

(*c*) The transfer and adaptation of basic knowledge from other fields of materials science, such as metallurgy and high temperature formed ceramics, will lead to better exploitation of the hydraulic properties of cement. (See figure 2, plate 1.)

(*d*) A branch of ceramic science and engineering dealing with formation of products by hydrothermal reactions will be developed. It will encompass cement use and its progress will be closely linked to progress in other areas involving reaction formed ceramics such as silicon nitride (Jennings 1982). (See figure 3, plate 1.)

(*e*) Improved understanding of factors affecting cement performance and more precise and meaningful characterizations of cements will greatly enhance knowledge of the relations between manufacturing conditions and cement performance. This will lead to new opportunities to optimize cement manufacturing processes in respect to energy use, product performance, and economy.

(*f*) The range of attainable mechanical properties of concrete will be much greater than is generally recognized as being possible at present. Much greater precision in predicting the performance of concrete will result in greater ability to design concrete to match the requirements for a given application.

(*g*) Greater emphasis will be placed on specifying the reliability of concretes intended to have specific service lives in specific service environments.

Table 1. Areas that need improvement in specific properties of concrete

	compressive strength	flexural or tensile strength	bond strength	volume stability	controlled expansion	uniform appearance	colour	low density	flow properties	Young modulus	impact resistance	ductility	engery absorption	fracture toughness
actory fabricated units														
. block	×	.	.	×	.	×	×	×	.	.	×	.	.	.
. brick	×	.	.	×	.	×	.	.	.	.	×	.	.	.
. pipe	×	×	.	×	.	.	.	.	.	.	×	.	.	×
. panels	.	×	.	×	.	×	×	×	.	.	×	.	.	×
. beams	×	×	.	×	.	.	.	.	.	×	.	×	.	×
. tile	.	×	.	.	.	×	.	×	×	.	×	.	.	.
. extruded products	.	×	.	×	.	×	.	.	×	.	×	.	×	×
. fibre-reinforced products	.	×	.	×	.	×	.	.	×	.	×	×	×	×
. boats	.	×	.	×	.	.	.	×	.	.	×	.	.	.
. railroad ties	.	×	.	.	.	.	.	.	.	.	×	×	×	×
ld use														
. foundations	×	×	.	.	.	.	.	.	.	.	.	.	.	.
. missile silos	×	×	.	×	.	.	.	.	.	.	×	.	×	×
. columns	×	×	.	.	.	×	.	.	.	×	.	.	.	.
. slabs	.	×	.	×	.	.	.	×	.	.	.	.	.	.
. highways	.	×	.	×	.	.	.	.	×	.	.	.	.	.
. canal linings	.	×	.	×	.	.	.	.	×	.	.	.	.	×
. tunnel linings	×	×	.	×	.	.	.	.	×	.	×	×	.	.
. bridge decks	.	×	.	×	.	.	.	.	.	.	.	.	.	.
. desalination plants	.	.	.	×	.	.	.	.	.	.	.	.	.	.
. dams	×	.	.	×	.	.	.	.	.	.	.	.	.	.
. marine construction	×	×	.	×	.	.	.	.	.	.	.	.	.	.
. nuclear press vessels	×	×	.	×	.	.	.	.	×	.	.	.	.	.
. terazzo	.	×	×	×	.	×	.	.	.	.	.	.	.	.
. stucco	.	×	×	×	.	×	.	.	×	.	×	.	.	.
. masonry mortar	×	.	×	×	.	.	.	.	×	.	.	.	.	.
. oil well grouts	.	.	×	×	.	.	.	.	×	.	.	.	.	.
. concrete patching	.	.	×	×	.	.	.	.	.	.	.	.	.	.
. refractory linings	.	.	×	×	.	.	.	×	×	.	.	.	.	×
. roofing	.	×	×	×	.	×	.	×	×	.	×	.	.	.
. elevated railroad structures	×	×	×	.	.	×	.	.	.	.	×	×	.	×
. hardened MX missile sites	×	×	×	.	.	.	.	.	.	.	×	×	×	×

early strength	quick setting	low heat liberation	low permeability	freeze–thaw resistance	sulphate and salt resistance	low thermal expansion	abrasion resistance	stain resistance	low thermal conductivity	high temperature resistance	low cost	estimate of fraction of total quantity of cement used	alternative materials
×	.	.	×	.	.	.	.	.	×	.	.	4	1. clay brick, adobe
.	.	.	.	.	.	.	.	.	×	.	.	0.2	2. clay brick
×	×	.	×	.	×	.	×	.	.	.	.	2	3. steel, asbestos with cement, plastic, Techite, clay
×	.	.	.	.	.	×	.	×	.	.	.	2	4. clay brick
×	×	.	.	.	.	×	.	.	.	.	.	2	5. steel, lumber
×	×	.	×	×	.	.	.	×	.	.	.	0.5	6. clay, tiles, slate, asbestos with cement, wood shingles
×	×	.	×	.	.	.	.	.	.	.	.	0.2	7. aluminum, steel, wood, plastic
×	×	.	×	.	×	×	.	.	.	.	.	2	8. aluminum, steel, wood, plastic, glass, fired clay
.	.	.	×	×	×	×	.	.	.	.	.	0.1	9. steel, wood
×	×	.	.	×	×	.	×	.	.	.	×	0.5	10. wood
.	.	×	.	.	×	.	.	.	.	.	×	40	1.
.	.	×	×	×	×	.	.	.	.	×	.	0.2	2.
.	.	.	.	.	.	.	.	.	.	.	.	8	3. steel
.	.	.	×	×	×	.	.	.	.	.	.	15	4.
.	.	.	×	×	×	×	×	.	.	.	×	15	5. asphalt
.	.	.	×	×	×	×	×	.	.	.	×	2.5	6.
×	×	.	×	.	×	×	×	.	.	.	×	2.0	7.
.	.	.	.	×	×	×	×	.	×	.	.	1.5	8. asphalt
.	.	.	×	.	×	×	×	.	×	.	.	0.1	9. metal, plastic, glass
.	.	×	.	×	×	×	.	.	.	.	×	0.7	10. earth fill
.	.	.	×	×	×	×	×	.	.	.	.	1.1	11. steel
.	.	×	.	.	.	×	.	.	.	×	.	0.1	12. steel
×	×	.	×	.	.	×	×	×	.	.	.	0.1	13. resins
.	.	.	×	.	.	.	.	×	.	.	.	0.5	14.
.	.	.	.	×	.	×	.	.	.	.	.	4.5	15. resin formulations
.	.	.	.	.	×	.	.	.	.	×	.	1.4	16.
×	×	.	.	×	×	×	×	.	.	.	.	0.1	17. resin formulations, asphalt
×	×	×	.	.	.	×	×	.	×	×	.	0.1	18. high alumina cement
.	.	.	.	×	.	×	.	.	.	.	.	0.1	19. asphalt, metal
.	.	.	.	×	×	.	.	.	.	.	.	0.5	20. steel
.	.	.	×	×	.	.	.	.	.	.	×	large	21. steel

(*h*) Cement standards will emphasize evaluation of performance and uniformity, and prediction of performance under varying conditions. Performance specifications will revive the incentive to develop proprietary cements and concretes.

(*i*) Understanding of factors affecting the performance of cements and concretes will make possible more rational decisions about the use of waste and by-product materials such as fly ash, blast-furnace slag, and silica fume in cement and concrete. Much more of these and other similar materials will be used in concrete.

(*j*) Computer-based aids to decision-making and sophisticated quality assurance programs will lead to improved cement formulations and improved cement manufacturing operations. Improved ability to assess quality will result in stronger incentives to improve the quality and uniformity of cements and concretes.

(*k*) Advances in cement technology will require more sophisticated technologists. Large data bases and mathematical models will aid the development of special academic training programs and provide ever-present opportunities for computer-aided individual instruction.

(*l*) International technical societies, aided by advances in telecommunications and distributed computing, will play a vital role in fostering worldwide collaboration among scientists involved with cement and concrete.

If, as we believe, these possibilities are desirable, we must ask how we may expedite their attainment. Let us now look at the scientific and technical needs, and then consider the needs for standards and education.

Scientific and technical needs

The challenges and opportunities facing the large element of the construction industry that uses cement are enormous considering the gaps in knowledge of factors affecting performance of cement in concrete (Sereda & Ramachandran 1975*a*, *b*). Our comments on gaps to be filled will apply specifically to Portland cements, but analogous statements can be made about other cementitious materials.

Before discussing the gaps in knowledge related to cement use and cement manufacture, we must note the common gap of how to characterize cement, its precursors and hydration products, in unambiguous terms related to performance. Inadequate ability to characterize the materials causes much of the effort to understand the manufacture and use of cements to be wasted.

The gaps in knowledge relating to cement characterization prevent us from being able to answer such questions as: what information is needed to describe a cement adequately for the purposes of (*a*) research ,(*b*) specifications and (*c*) making decisions concerning suitability for a given application? How can the information be obtained at a reasonable cost? The magnitude of the knowledge gap is apparent from the collective inability of scientists to answer satisfactorily some obvious questions about any cement, or even to agree on the relative importance of the questions. Examples of the questions that might be asked about a cement are: what is its particle size distribution? What is its elemental composition? What phases are present and how much is there of each? What are the compositions of the phases? What are the types and concentrations of the imperfections in the various phases? How are the phases distributed between the particles of different sizes? What are the natures of the particle surfaces?

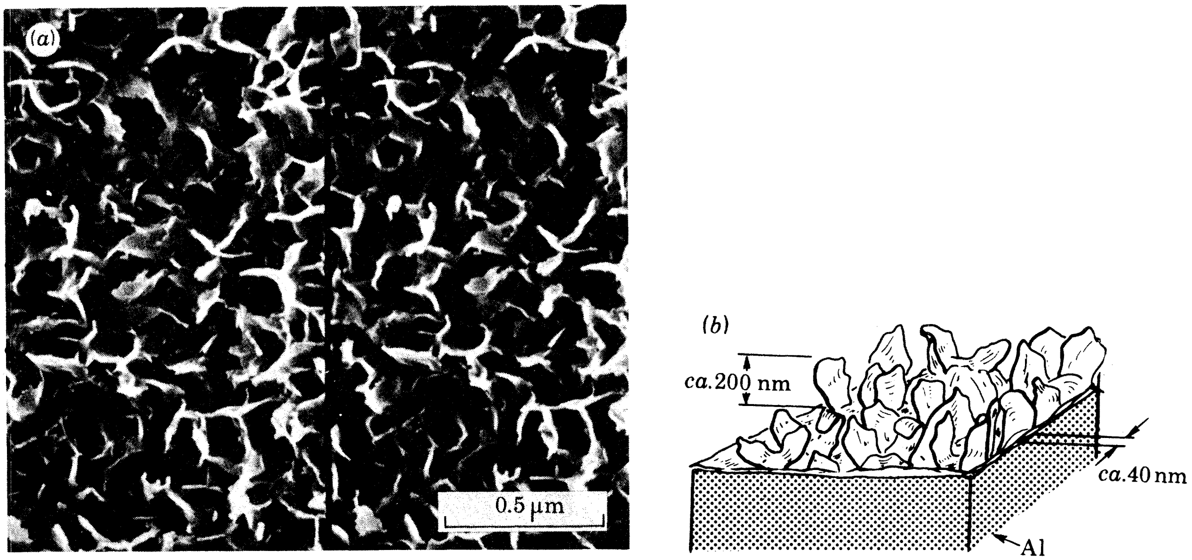

FIGURE 2. Analogies between the reactions of cement and other materials may contribute to an understanding of the reaction mechanisms and structure formation. For example, this high resolution stereo s.e.m. micrograph (*a*) and schematic drawing (*b*) of $Al(OH)_3$ show a 'honeycomb' morphology (Venables *et al.* 1980) resembling that of gel formed in the early minutes of $Ca_3Al_2O_6$ hydration (Breval 1976). Similar to hydration of cement components, Al_2O_3 hydration exhibits an induction period that can be modified by dissolved additives.

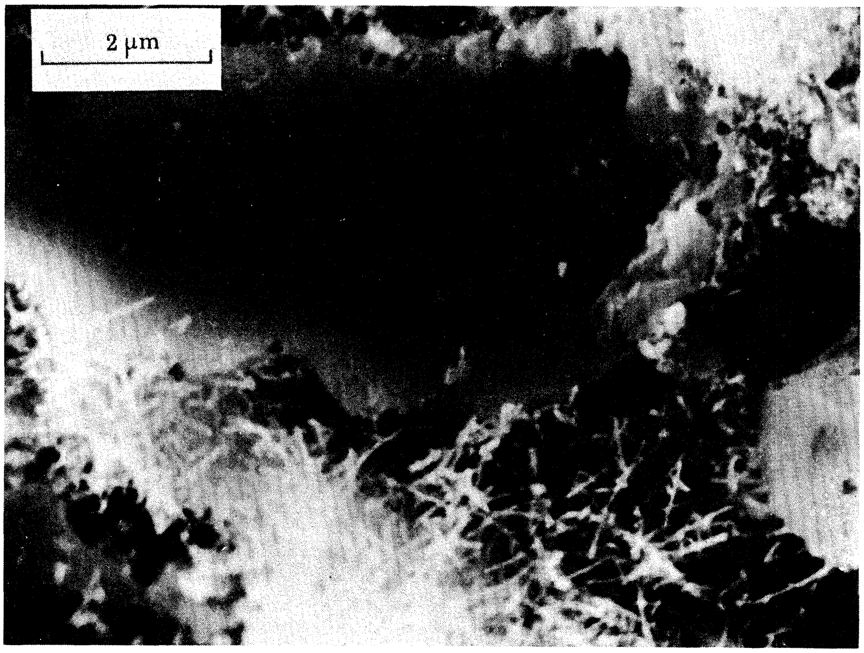

FIGURE 3. S.e.m. micrograph of silicon nitride showing a similar micromorphology of that of a cement paste at an early stage of hydration (Jennings 1982). This resemblance – as well as other similarities to reaction-formed ceramics (for example, induction periods, 'inner' and 'outer' products, brittleness) – may be the result of similar reaction mechanisms.

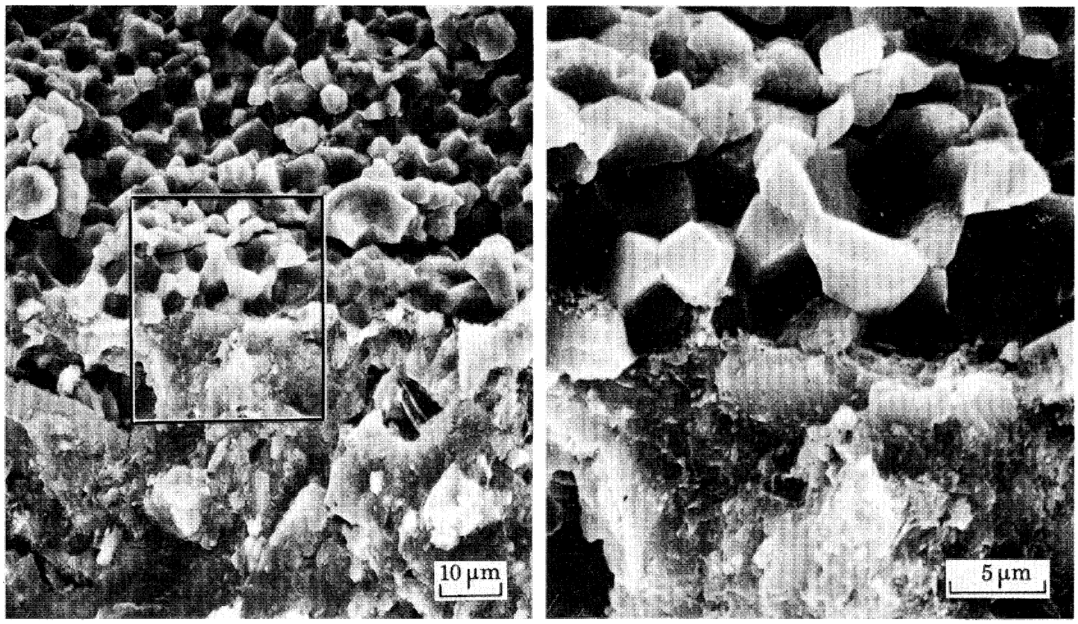

FIGURE 4. There are many unanswered questions about the cement paste–aggregate bond and its effects on concrete performance. These s.e.m. micrographs show the interface of a cement paste – quartz composite fractured normal to the interface. In contrast to samples made with limestone, calcium hydroxide cannot be seen in the 'aureole de transition' and the paste at the interface appears to have about the same porosity as the bulk cement paste (Mindess & Struble 1982).

FIGURE 6. Improvements in cements and concretes can lead to improvements in civil engineering. The Water Tower Place in Chicago is the world's tallest reinforced concrete frame building (*ca.* 260 m). The structural columns of its lower floors were constructed with 62 MPa (90 days) ready-mixed concrete, which was not available until about 10 years ago.

Cement use

There are uncertainties not only about the quantitative relations between measurable characteristics of anhydrous cements and their contributions to the engineering performance of concrete, but also often about the qualitative relations. The uncertainties particularly concern factors affecting durability and other aspects of long-term performance. There is a challenge to define the factors controlling the engineering properties of hardened cement pastes in concrete and to express the information in the form of mathematical models which can help reduce the uncertainties. This was attempted for sulphate resistance by Dunstan (1982). Examples of needed individual models, which might ultimately become part of a comprehensive macromodel of cement manufacture and use (Frohnsdorff & Clifton 1981), are models relating cement characteristics to (*a*) cement hydration and microstructure formation; (*b*) environmental effects on hardened cement pastes; (*c*) rheological behaviour of fresh cement pastes, including the effects of shear on the subsequent properties of hardened pastes; (*d*) the reactions of cement pastes with aggregates and mineral admixtures, including the chemistry and physics of the paste–aggregate bond; and (*e*) the micro- and macro-structures of hardened cement pastes and their relation to the engineering performance of concrete. The models should extend to the undoubtedly very complex and challenging examples of cement pastes and concretes containing chemical and mineral admixtures.

Examples of significant gaps in knowledge relating to cement use have been provided by recent conferences on the rheology of concrete and on the cement paste–aggregate bond. The participants in the Materials Research Society Symposium on concrete rheology (Skalny 1982) agreed that lack of knowledge of rheological properties (as well as inadequate dissemination of existing knowledge) is hindering development of concrete processing equipment and, hence, hindering the progress of concrete technology. They believed that new processing techniques, based on recent research, could lead to concrete that would be easy to place even at low water contents, and have much higher strengths than are now attainable, and have greater durability. This suggests that closing gaps in this area of knowledge should make it possible to decrease the life-cycle cost:benefit ratios of concrete structures, whether through using concrete closer to its theoretical limits, or by increasing the safety factors and, hence, the service life.

For the cement paste–aggregate bond (Struble *et al.* 1979), the common belief that the ‘bond’, however defined, is often the strength-limiting factor in concrete has been brought into doubt by presentations at two recent international conferences on bonding (Bartos 1982; I.N.S.I. 1982). Other opinions that the bond may not be the ‘weak link’ rest on the following evidence: (*a*) the paste–aggregate interface does not necessarily provide an easy pathway for water flow (Mindess & Struble 1982; Wakeley & Roy 1982); (*b*) whereas damage at or near the paste–aggregate interface, such as the formation of drying cracks, reduces strength, it has not been shown that improvement of the bond will increase strength; and (*c*) since the paste in concrete is usually confined between quite closely packed, mechanically stronger, grains of sand and aggregate, the fact that a crack propagates through, or close to, the paste–aggregate interface is not conclusive evidence of weakness of the bond (Diamond *et al.* 1982). It is clear that answering many questions relating to the nature of the bond, its importance to the performance of concrete, and the effects of the cement upon it, remains a challenge. (see figure 4, plate 2.)

Research has contributed significantly to most of the technological advances in cement and concrete. Among the recent contributions that are likely to have strong influences on the cement and concrete technology in the 1990s are knowledge of water reducing and super-water reducing admixtures (Hattori *et al.* 1964), macro-defect-free cement pastes (Birchall *et al.* 1981), concretes containing well dispersed, ultrafine particles (Bache 1981) or ground blast-furnace slag (Roy & Idorn 1982), and the cement–aggregate bond. It is noteworthy that all of these confirm the insights of earlier scientists (for example, Feret 1892, 1906; Abrams 1918; Davis 1937; Powers & Brownyard 1948; Kaplan 1961; Lott & Kesler 1966; Yudenfreund *et al.* 1972). They are evidence that opportunities abound, even though we may be slow to recognize and exploit them.

Cement production

Turning to cement manufacture, we do not yet know how to optimize the steps in cement production, individually or collectively, so as to produce the highest quality, most economical, or most uniform product (Roy 1980). Specifically, because of gaps in knowledge, we do not know with certainty: (*a*) how to define the quality of a clinker; (*b*) the relations between the mineralogy of the raw materials and the economy of their transformation into clinker of a given quality; (*c*) the effects of minor components on the clinkering reactions and clinker quality; (*d*) the effects of the kiln environment on clinker quality; (*e*) how to optimize heat transfer between burning fuel and kiln feed (see figure 5); (*f*) how to predict the effects of grinding on particle size and size distribution and how to optimize comminution processes; (*g*) how to predict the effects of time and conditions of cement storage on the performance of cements; and (*h*) what measurements of raw materials and products are needed, or how they should be made to provide feedback for optimal process control.

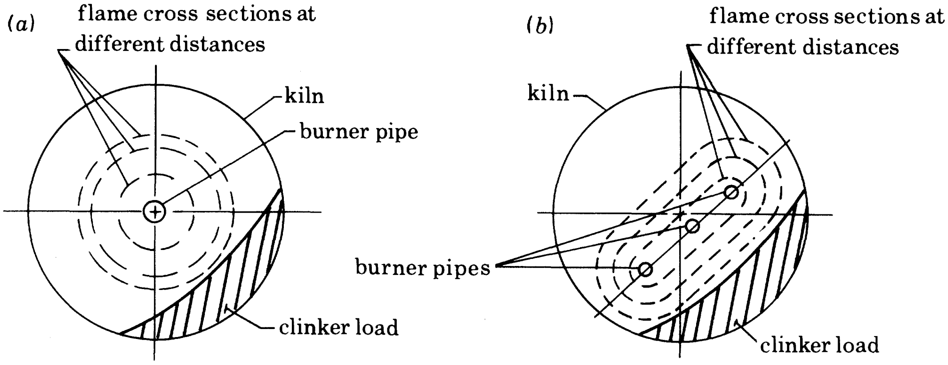

FIGURE 5. New engineering ideas could lead to improved energy efficiency in clinker production and more uniform cement. For example, the usual, approximately axisymmetric flame cross section (*a*) in rotary kilns might be replaced by an elliptical cross section (*b*) by varying the number, spacing, and orientation of the burner pipes (Weil 1983; personal communication). This should lead to better heat transfer and better control of clinker quality. The optimum geometry for such an arrangement would be arrived at by a combination of computer modelling and experimentation.

The costs of filling the gaps in knowledge of cement manufacture will be high, but the challenge must be met. We strongly believe that improvements in control of cement production processes will lead to improved cement quality, including uniformity, and better use of the chemical energy stored in cements (Idorn 1980). The benefits will include improved engineering performance of traditional products (see figure 6), better utilization of energy and natural resources, new applications of cement and, most important, reduction in life-cycle cost: benefit ratios of concrete structures.

While the filling of gaps in knowledge of cement science and technology is essential, the technology is so closely tied to standard tests and specifications (Mehta 1978) that possible modification of cement standards must now be discussed.

Cement standards

Although engineers and building officials must have basically similar performance requirements for cements, standard cement specifications for different countries are often significantly different. For example, comparison of ASTM and British standards for sulphate-resisting cements (ASTM C-150 and BS 4027) shows that it may be impossible for any single cement to meet both standards simultaneously and suggests that, in the unlikely event that one of the standards is optimal, the other must be either too restrictive or too lax. The important question, 'Which standard is better?' is difficult to resolve because, at present, there is no generally accepted performance test for sulphate-resistance nor any widely accepted basis for predicting sulphate resistance (other than compliance with these or other national standards).

For blended cements made from Portland cement clinker and either a pozzolan, such as fly ash, or a blast-furnace slag, inconsistencies among standards appear to be greater than for sulphate-resisting Portland cements. National standards differ greatly in the compositional ranges used as the basis for classification of blended cements (*Cement standards of the world* 1968).

For the most part, cement standards have both prescriptive and performance requirements. The prescriptive requirements often appear to be unnecessarily restrictive and to preclude the use of some compositions that would perform satisfactorily. For this reason, there is interest in writing certain cement standards exclusively in performance terms. While it is generally agreed that performance standards should at least be available as an option, the difficulties and the time needed to prepare them should not be underestimated. For example, whereas an editorial or other minor change in an ASTM cement standard can often be achieved within a year, many more years, perhaps 5–15, might be needed to make a really substantial change. At the risk of oversimplification, the delay occurs because it is difficult to reach a consensus among committee members when there are gaps in the data needed to make a convincing case that the benefits of a proposed change will outweight the possible risks. In the present state of knowledge, significant gaps are inevitable.

Despite the difficulties, good progress is being made towards the establishment of an ASTM performance standard for blended cements. If the activity, which has already taken eight years, is successful it should open up opportunities for manufacture of blended cements of new compositions. An essential complementary activity to the development of a performance standard is the development of needed tests, particularly tests related to durability, for example, sulphate resistance.

We believe a workable performance specification for structural cements will be established by ASTM by the 1990s, and that it will provide new incentives for cement research. It could stimulate research on new formulations, particularly those containing waste or by-product materials such as fly ash and blast-furnace slag, and also other less obvious ingredients. Further, because of the challenge of minimizing costly and time-consuming performance testing, it will stimulate improvement of performance tests and the ability to predict performance from knowledge of the cement characteristics and the expected service environment. The movement to performance specifications could aid the harmonization of cement specifications among different countries. A substantial fundamental research effort will be needed to achieve the full benefits from performance specifications, but once tangible signs of progress are seen, the potential benefits should generate increased support for research.

Education of technologists working with cement and dissemination of knowledge

Because of the complexity and multidisciplinary nature of the problems to be solved, cement research places great demands on the researcher and on those who wish to make practical use of the research results. Consistent with the low level of cement research, at least in the U.S., no institution of higher learning offers a comprehensive range of courses in cement science and technology. This situation must change if the cement and concrete industries are to achieve their full potential. Some signs of change can be seen. For example, audio-visual and computer-based teaching aids are being developed through professional societies like the American Concrete Institute and through the *Journal of Educational Modules in Materials Science and Engineering*; also there should be high educational value to the comprehensive mathematical models linking cement chemistry and physics to the physical and mechanical properties of concrete, which are being developed (Pommersheim & Clifton 1980; Popovics 1976).

Closely related to the education of technologists and the impact they will make on the cement technology of the 1990s will be their ease of access to large data bases. The progress now being made in the generation and management of data bases of all sorts (Date 1981), when coupled with ability to evaluate data against mathematical models representing the state of the art, will bring a new vitality to cement and concrete technology, partly because interdisciplinary barriers will break down.

Improvements in education and communications are likely to be the most effective avenues for advancing the knowledge of cement science and technology. They should make it possible to coordinate the present highly fragmented, inadequate cement research efforts on an international basis. An encouraging example of what can be done is provided by the recently formed RILEM Committee 68–MMH on Mathematical Modelling of Cement Hydration, which is developing conceptual models of cement hydration reactions that could become the basis for mathematical models capable of solution by computer. The potential impact on cement science appears to be great, since it is encouraging a substantial number of leading scientists, working with cement, to interact more directly and positively than ever before in the search for a unified theory of cement hydration. The knowledge gained should have a worldwide impact on cement and concrete technology by providing a basis for improving the following: techniques for predicting cement performances; tests of cement performance and uniformity; microstructural engineering to optimize performance of cement in concrete; education of scientists and technologists; cement specifications; and research plans.

The RILEM committee cannot address all the problems that could benefit from international collaboration. It can, however, indicate the potential benefits to be achieved through collaboration. These are likely to be amplified through the growing availability of computers, computer software and telecommunications.

CONCLUDING REMARKS

There are many gaps in knowledge of cement science and many barriers to innovation in cement technology. Among barriers mentioned in the N.M.A.B. report (Roy 1980) were: complexity of the scientific and technical problems; lack of understanding of technical possibilities for progress; fragmentation, inadequate focus, and discontinuity of research efforts; inadequate mechanisms for productive and timely exchange of ideas among scientists and, more importantly, between basic research and users of the developed ideas; commodity nature of the cement and concrete industries and their low-technology image; improbability of short term return on investment in cement research; unsuitability of the patent system for providing incentives for investment in cement research; lack of performance-based standards and specifications; and inadequate specialized education of technologists working with cement and concrete.

Despite the gaps in knowledge and the barriers to innovation, there are increasingly good opportunities for making cement and concrete more valuable and versatile materials by improving the uniformity of cements; the ability to predict cement performance from measurable chemical and physical characteristics; and the knowledge of factors affecting cement performance, even for cements outside the current range of commercial manufacture.

Since fundamental cement and concrete research activities are so fragmented, it is questionable whether an adequate number of specialized scientists with all the requisite skills is to be found in any single organization. If this is so, some new institutional mechanisms are needed to change this. Among the possible mechanisms is increased collaboration on an international level, either informally or under the auspices of an international technical society. The collaboration would involve development of research agendas and plans, and timely sharing of research results. This idea takes on real significance at this time when specialized data bases are becoming practicable and mathematical models show promise of developing as concise representations of the state of knowledge of cementing reactions and the associated changes in physical mechanical properties. Increasing the level of collaboration poses a challenge and offers opportunities for filling the gaps in knowledge of cement science and overcoming the present barriers to progress.

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Discussion

B. A. PROCTOR (*Pilkington Brothers p.l.c., Ormskirk, Lancashire, U.K.*). I have become increasingly doubtful that performance standards can, by themselves, be adequate and satisfactory. The reason for this doubt lies in the multiplicity of performance requirements required from a material and often only implied in the actual standard itself. However, in a 'recipe' standard it is known from experience that a material conforming to that description will perform a number of functions adequately in a wide variety of conditions. For example, we do not only wish to know the strength of concrete – which might be covered by a performance specification but met by a number of cements and mixes – but we also wish to know that it will retain that strength in freeze–thaw or marine conditions, not be too porous, not corrode the steel, etc. Factors covered by (say) using cement to BS 12 and a well-proven mix.

I wonder whether others share my doubts that performance standards can provide all the answers in the future, and my feeling that 'recipe specifications' still have a significant and vital role to play.

J. P. Skalny. Mr Proctor's scepticism is well taken: we do have many technical barriers to overcome before performance specifications become generally acceptable and some aspects of specifications may (and should) remain prescriptive for a long time. However, we believe that, with increasing understanding of the relation between the composition, microstructure, and physical performance, the trend will be largely towards performance specification. The use of modern computer techniques and modelling will help in their development and acceptance.

A. Kelly, F.R.S. (*University of Surrey, U.K.*). Standards-writing bodies specifically eschew the notion of fitness-for-purpose when writing standards. The first questioner had, I thought, a very good suggestion to make, but to follow it will require a change of philosophy among standards-writing bodies.

J. P. Skalny. I wish to comment on Dr Kelly's first point. I think this has been generally true, but that changes are taking place in the standards process. It has been customary to separate specifications from test methods in standards and to exclude fitness-for-purpose, specifically relating to durability, from the specification. For cements, this was satisfactory as long as all cements fell into a relative-narrow range of compositions with a relatively-narrow range of behaviours. The situation has to change when the need to introduce new compositions, for whatever reason, becomes sufficiently great. At this point, the comparative performance of cements of different types has to be able to be evaluated. At least in the United States, it is government policy to encourage the writing of performance specification as a way of minimizing barriers to innovation. There is no question that it is difficult, but the benefits are recognized by standards bodies, as well as governmental agencies.

F. Tamàs (*Department of Silicate Chemistry, University of Veszprem, Hungary*). Dr Skalny mentioned the importance of bond between cement paste and aggregate. Could this somehow explain the high compressive strength of concretes with carbonaceous aggregate (crushed limestone or dolomite), as contrasted with ordinary (siliceous) aggregate, especially at relatively early ages?

J. P. Skalny. There is still much to be learned about the bond between paste and aggregate. It is widely accepted that limestone aggregates form a reaction layer on the surfaces when in contact with Portland cement paste. We think it possible that the product of the paste–aggregate reaction could account for differences in behaviour between carbonate and silicate aggregates.

L. McCurrich (*Fosroc Technology Ltd, Central Laboratory, Leighton Buzzard, U.K.*). It would be interesting if Dr Skalny could speculate about developments in cement technology to improve dimensional stability. Dr Pomeroy previously spoke about cement-based machine parts but I remember that for the concrete generator stators produced some years ago, they had to be given vacuum treatment and polymer impregnation to improve long term dimensional stability.

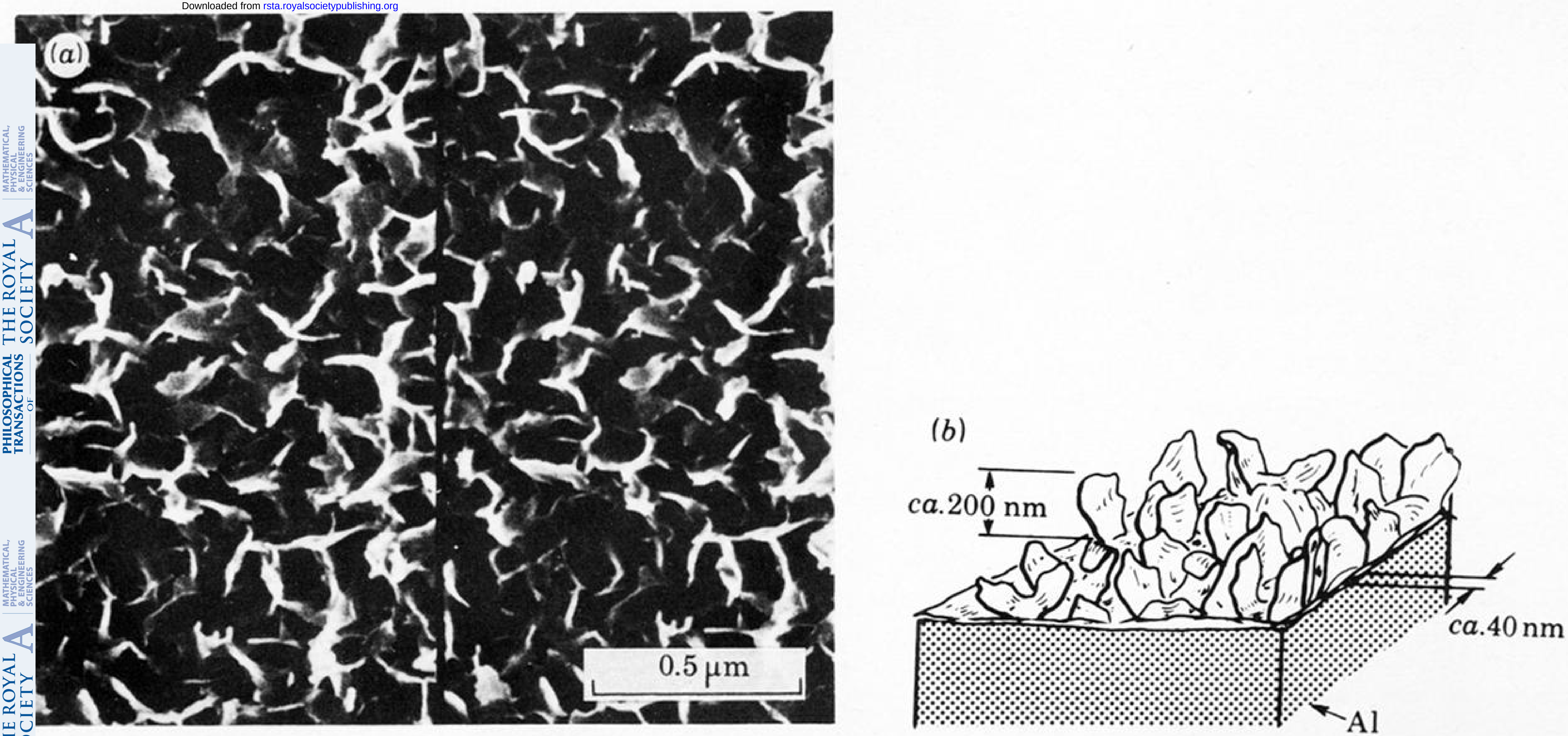
Much of the early work on shrinkage-compensating cements originated in the U.S.A. It would be interesting if Dr Skalny could comment on their status in the U.S.A. today and on future developments in shrinkage-compensating cement.

J. P. Skalny. Dimensional changes of cementitious systems reflect changes in temperature, and changes in moisture content. This is in addition to any effects from volume changes caused by chemical reactions like those in shrinkage-compensating cements. Dealing with the drying shrinkage, it has been shown that the effects are minimized if the cement is maintained at an optimum SO_3 content since cement with an SO_3 content of 0.5 % less than the optimum could have a drying shrinkage 10–25 % greater than a corresponding cement with the optimum SO_3 content. There are no clear separations in shrinkage potential between different types of Portland cements. In one study, shrinkages for different cements ranged from about 25 % less than the median value to 40–50 % above.

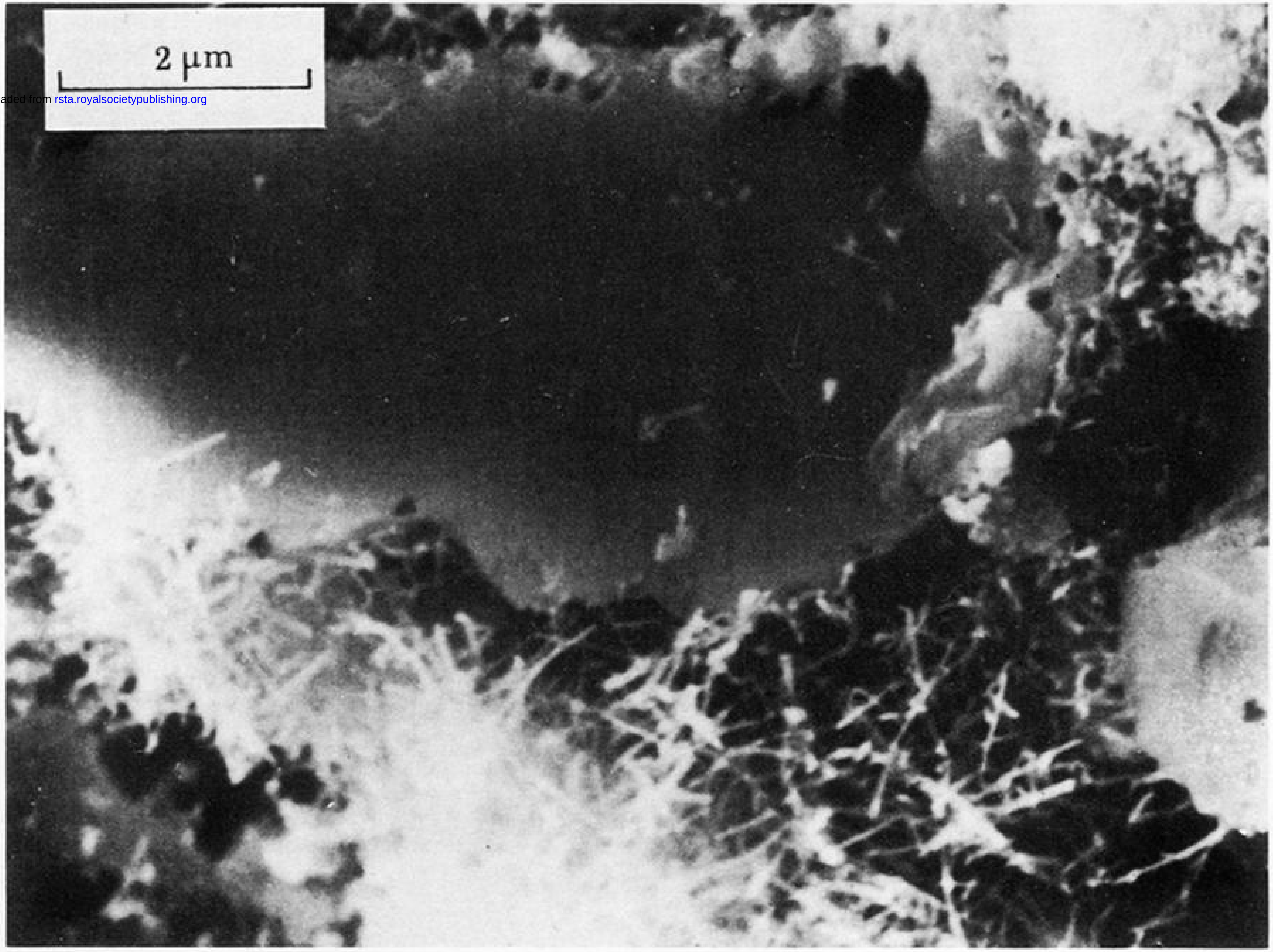
With regard to the future developments in shrinkage compensating cement – I'm afraid I cannot answer the question as I am only marginally familiar with the technical aspects of the issue.

P. Jackson (*The Rugby Portland Cement p.l.c., Rugby, U.K.*). Would Dr Skalny indicate the level of expenditure (as a percentage of turnover) that the industries involved should adopt to achieve an adequate level of progress towards the objectives he has outlined?

J. P. Skalny. This is a difficult question to answer, but the level of expenditure should certainly be well above the presently estimated 0.1 % of sales (0.01 % for basic R. and D.). And it is not only the funds! More importantly, long-term research needs good management, stability, and moral support from above (corporate and governmental).



IGURE 2. Analogies between the reactions of cement and other materials may contribute to an understanding of the reaction mechanisms and structure formation. For example, this high resolution stereo s.e.m. micrograph (*a*) and schematic drawing (*b*) of $Al(OH)_3$ show a 'honeycomb' morphology (Venables *et al.* 1980) resembling that of gel formed in the early minutes of $Ca_3Al_2O_6$ hydration (Breval 1976). Similar to hydration of cement components, Al_2O_3 hydration exhibits an induction period that can be modified by dissolved additives.



IGURE 3. S.e.m. micrograph of silicon nitride showing a similar micromorphology of that of a cement paste at an early stage of hydration (Jennings 1982). This resemblance – as well as other similarities to reaction-formed ceramics (for example, induction periods, 'inner' and 'outer' products, brittleness) – may be the result of similar reaction mechanisms.

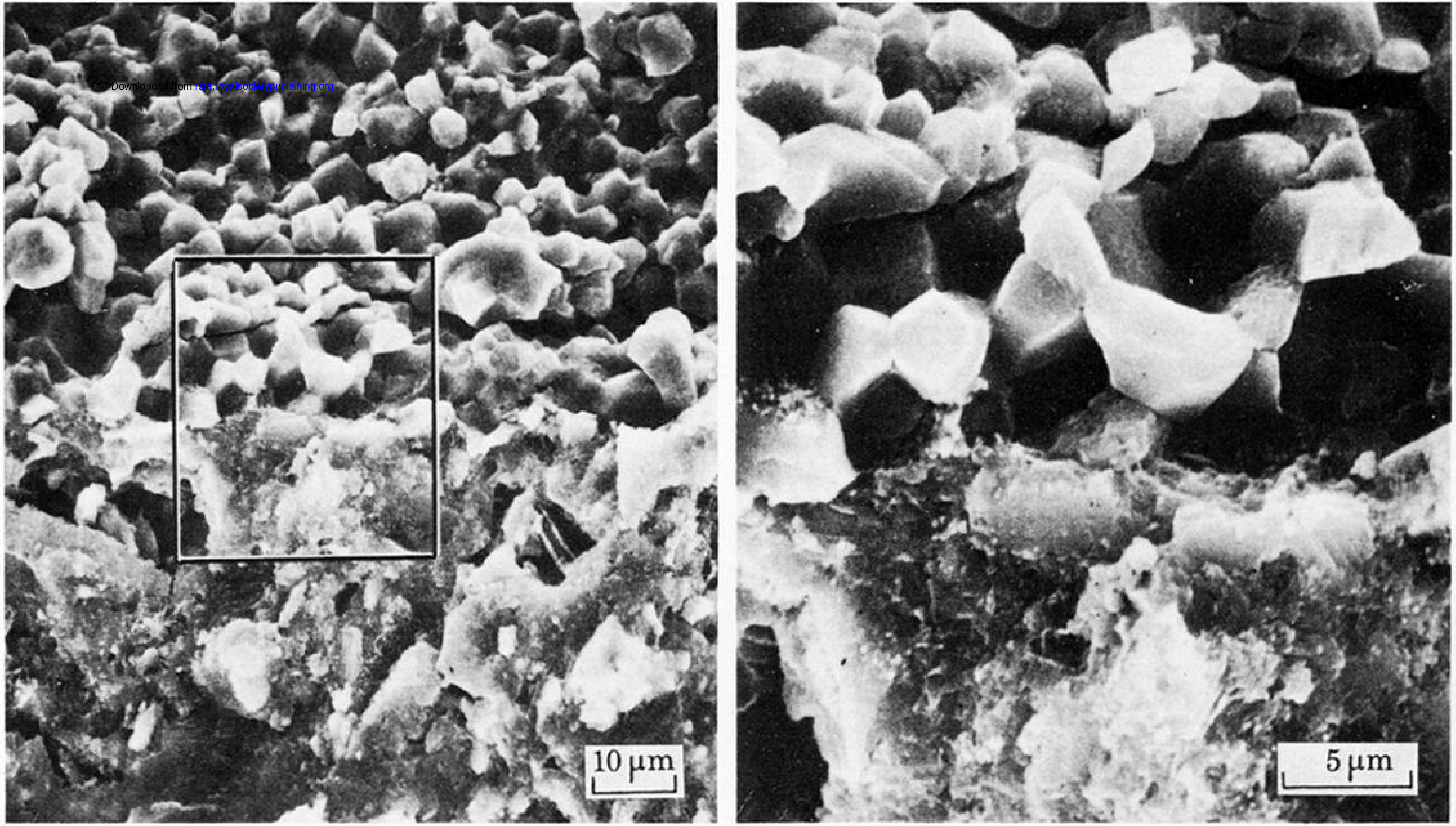
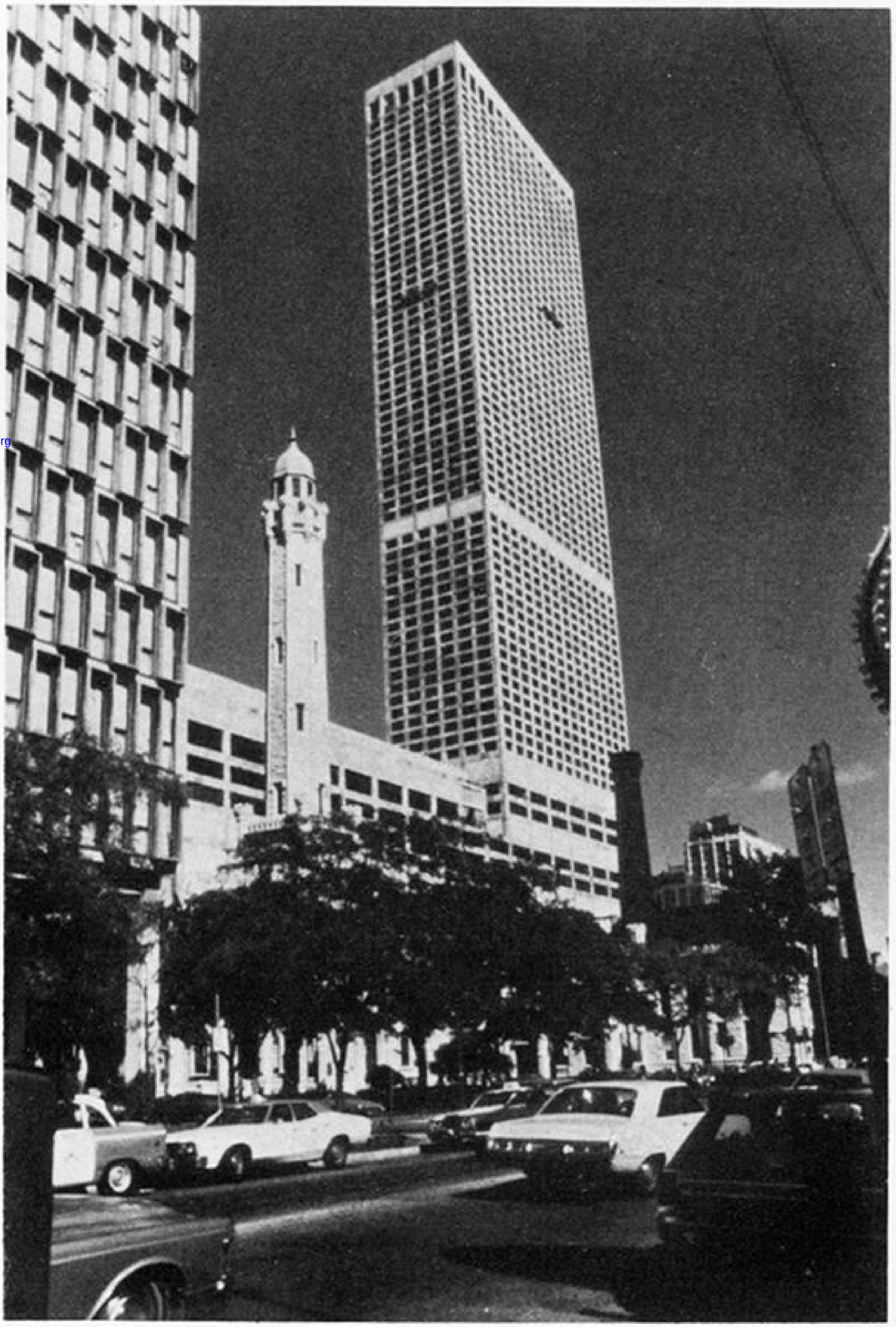


FIGURE 4. There are many unanswered questions about the cement paste–aggregate bond and its effects on concrete performance. These s.e.m. micrographs show the interface of a cement paste – quartz composite fractured normal to the interface. In contrast to samples made with limestone, calcium hydroxide cannot be seen in the 'aureole de transition' and the paste at the interface appears to have about the same porosity as the bulk cement paste (Mindess & Struble 1982).



IGURE 6. Improvements in cements and concretes can lead to improvements in civil engineering. The Water Tower Place in Chicago is the world's tallest reinforced concrete frame building (*ca.* 260 m). The structural columns of its lower floors were constructed with 62 MPa (90 days) ready-mixed concrete, which was not available until about 10 years ago.