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Trends in Building Materials Research

by V.S. Ramachandran and H.E. Ashton

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ABSTRACT

Several aspects of building materials research that should receive more attention are discussed. The behaviour of materials is related to the physical and chemical properties of the basic ingredients and these need to be characterized properly. There is an increasing need to utilize waste and by-products and those that are not being used presently could be used after some treatments. Research efforts should also be directed to develop new materials with better mechanical properties. Although tests have been used to predict the performance of materials, many of them are not related to the actual conditions to which materials are exposed in natural weathering. Because of the possibility of various pollutants affecting the surface of materials, efforts should be made to relate the type and concentration of pollutants to their effect on materials. Many buildings have low air-infiltration characteristics, causing health hazards due to pollutants such as radon and its decay products, and formaldehyde and other organic contaminants. Monitoring of these contaminants and studying their effect on health should receive more attention. Where sufficient information on materials is available, attempts should be made to develop mathematical models to bridge the gap between science and technology.

RÉSUMÉ

Ce document porte sur plusieurs aspects de la recherche sur les matériaux de construction qui devraient recevoir une plus grande attention. Le comportement des matériaux est lié à leurs propriétés physiques et chimiques. Il faut bien caractériser ces propriétés. Les sous-produits et les déchets et ceux qui ne sont pas à l'heure actuelle pourrissent devraient être utilisés après des traitements. Les efforts de recherche devraient être dirigés vers le développement de nouveaux matériaux avec de meilleures propriétés mécaniques et physiques. Bien que des tests aient été utilisés pour prévoir la performance des matériaux, beaucoup d'entre eux ne reflètent pas les conditions réelles auxquelles les matériaux sont exposés. En raison de la possibilité que divers polluants affectent la surface des matériaux, il faudrait relier le type et la concentration des polluants à leur effet sur les matériaux. De nombreux bâtiments ont de faibles caractéristiques de infiltration d'air, causant des dangers pour la santé en raison de polluants tels que le radon et ses produits de décadence, et le formaldéhyde et d'autres contaminants organiques. Le suivi de ces contaminants et l'étude de leur effet sur la santé devraient recevoir plus d'attention. Lorsque l'on dispose de suffisamment d'information sur les matériaux, on devrait tenter de développer des modèles mathématiques pour combler le fossé entre la science et la technologie.

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We are proceeding with the publication of prospective article on diverse topics covered by the programme of the 1987 RILEM Congress: From materials science to materials engineering. In this issue, Dr. Ramachandran and Mr. Ashton, from the National Research Council Canada, are dealing with new trends in building materials research.

Dr. V. S. Ramachandran is Head, Building Materials Section, Institute for Research in Construction, National Research Council Canada.

Dr. V. S. Ramachandran has been engaged in research for 33 years and has made significant contributions in catalysis, clay mineralogy, lime, gypsum and cement chemistry and concrete technology. He has published five books: (i) Differential Thermal Analysis in Building Science; (ii) Application of DTA in Cement Chemistry; (iii) Calcium Chloride in Concrete; (iv) Concrete Science; (v) Concrete Admixtures Handbook. He has also contributed 13 chapters to books. He has published about 140 research papers. He is a co-author of the recently submitted book "Silica Fume in Concrete".

He is a Fellow of the Royal Society of Chemistry, Ceramic Society, UK, and the American Ceramic Society. He is a member of the American Society for Testing and Materials, American Concrete Institute, and the International Confederation of Thermal Analysis. He is a member of the Advisory Committee and a Chairman of a Technical Committee on Admixtures of RILEM.

Dr. Ramachandran was a nominee for the Mettler Award, instituted by the International Confederation of Thermal Analysis, USA. He received an award for outstanding work in concrete technology from the University of Nuevo Leon, Mexico.

Mr. H. E. Ashton, Assistant Head of the Building Materials Section, Institute for Research in Construction, National Research Council Canada, is a graduate of the University of British Columbia with an Honour BA in Chemistry. After working for ten years in industry, principally with the General Paint Corp., Vancouver, BC, he joined the former Division of Building Research (now IRC) in 1956.

He has been engaged in research on paint test methods, determining the properties required for clear finishes, stains and paints to perform adequately on wood, and establishing the basic principles for accelerated tests on organic materials. Publications cover subjects from evaluating the performance of organic building materials, to color standards for egg yolks, to one Canadian's views on ASTM.

He is a Fellow of ASTM and a recipient of the Pearce Award from ASTM Committee D-1 for outstanding work on the science of paint testing the Certificate of Merit from CGSB, Certificates of Appreciation from ASTM Committees D-1 and G-3, and the ASTM Certificate of Appreciation for editorial excellence.

Trends in building materials research

V. S. Ramachandran, and H. E. Ashton

INTRODUCTION

Materials form a substantial percentage of the total value of construction. In 1984 the value of all materials used in construction in Canada amounted to about \$21 billion, out of the total of \$56 billion in the value of construction put in place. In most countries construction accounts for a substantial percentage of GNP, in Canada's case about 14%. Fabrication and use of building elements require an understanding of

the materials and the climatic factors to which they are exposed.

Based on their experience, the authors present a brief review of some important aspects of building materials research that should receive more attention in the coming years: characterizing materials, utilizing wastes and by-products, developing new building materials, correctly assessing durability characteristics, formulating realistic standards, studying pollution effects on buildings, mathematical modelling, and evaluating air quality in buildings.

CHARACTERIZATION

Two raw materials apparently identical in all respects may show divergent physical and mechanical behaviours once they are processed under similar conditions to produce building materials intended for the same use. This observation points out the currently inadequate knowledge of the important factors that determine the properties of a material and the limitations of techniques used to identify the properties.

Surface area values of cement generally indicate the rate at which it will hydrate. The Blaine air permeability method, prescribed by ASTM for measuring surface areas, is practical but has limitations. Surface area determined for the same cement depends on the method used [1]. Using techniques such as Andreasen, Wagner, air permeability and nitrogen adsorption methods, type I cement may show values of 3,110, 2,270, 4,150 and 10,000 cm²/g, respectively. These results suggest that a simple and quick method does not necessarily yield reliable values.

Even using the same type of cement in concrete does not mean that similar strengths will be obtained, especially in combination with admixtures. Using the same type and amount of cement, air content, slump and percentage of calcium chloride admixture does not ensure that the influence of calcium chloride on strength will be the same for each batch. The effect of calcium chloride on the compressive strengths of 13 cements (all ASTM Type I) cured for 7 or 28 days has been studied [2]. Calcium chloride causes a slight to moderate increase in the 7-day compressive strengths of 11 out of 13 cements but a decrease at 28 days for 9 of the 13 cements compared to the compressive strengths of the corresponding reference mixes. These results show that characterizing cements according to the standards may not adequately predict their behaviour.

Attempts have been made to characterize porous building materials as a basis for predicting their mechanical properties. Characterization of cementitious materials using surface area, porosity, pore size distribution, density, microstructure and composition has met with varied success [3].

WASTE AND BY-PRODUCTS

Conservation of resources, environmental protection standards and judicious use of energy will create an interest in utilizing wastes and by-products, and recycling materials. Some potential materials are: fly ash, blast furnace slag and other slags, rice husk, mica, waste glass, condensed silica fumes, waste gypsum, waste rubber, limestone powder waste, sawdust, lignin, and demolition waste.

Since concrete made with portland cement, water and aggregates constitutes the greatest portion of all man-made materials, attempts are being made to incor-

porate wastes into it. Some of the materials may also be utilized to fabricate inorganic and organic building materials not based on portland cement.

A waste or by-product may be used as a raw material for the production of portland cement clinker, as a supplementary material in blended cements, as a substitute for chemical gypsum (an important ingredient of portland cement), admixture and aggregate.

In the production of portland cement, of a total energy of 6.06×10^6 J/kg, clinker formation accounts for 4.89×10^6 J/kg [4]. This energy can be decreased by using waste oils or municipal wastes or by adding certain ingredients to the raw mix. For example, by using phosphogypsum (a by-product of phosphoric acid manufacture) or fluorogypsum as a mineralizer, the clinkering temperature can be reduced by 200°C. However, possible adverse effects of this method on setting and strength need to be examined.

Fly ash or blast furnace slag can be blended with portland cement during grinding to reduce the energy that ultimately goes into making concrete. They may also be added to the concrete mix as separately dry-batched compounds or mixed as a water slurry with portland cement and aggregate when batching concrete. The resulting concrete possesses certain advantages over normal concrete: reduced alkali-aggregate expansion, better sulfate resistance, reduced segregation and bleeding, and better workability. By incorporating 30-40% fly ash the expansion due to alkali-aggregate reaction is reduced by more than 95% [5]. Although fly ash and blast furnace slag have had limited use in concrete, certain problems have prevented wider application. All fly ashes and slags are not equally active with respect to strength development and the factors responsible for this are not completely known. The relative roles of physical structure (crystalline or glassy nature), chemical composition, pore structure, surface area, particle size and shape, density and weight loss on ignition have yet to be clarified. A good accelerator to increase the rate of strength development in blended cement has still to be discovered. The dosage of air-entraining agent required to attain a known amount of air in concrete is not easy to predict when fly ash is used.

Utilizing wastes or by-products in concrete to replace normal aggregates, which make up 75% of the volume of concrete, will become much more common. Waste materials are divided into three groups based on their potential for use as aggregates [6], with Group I being the most viable. Demolition wastes containing concrete belong to this class. Because concrete is the major construction material, it should also account for most of the demolition waste. In fact, the production of such waste in the United States, the United Kingdom, Japan, Canada and Sweden runs to several million tonnes annually [7]. However, the compressive strength, modulus of elasticity and flexural strength of concrete containing recycled concrete are lower than in concrete made with normal aggregate. The partial replacement

of normal aggregate by wastes, the use of superplasticizers or other admixtures, and the cost-effective removal of contaminants that affect concrete properties all need to be investigated.

Group II wastes such as steel slag, waste glass and building rubble could be considered for application only after extensive research and development work. At present variability in their physical and chemical properties and transportation difficulties inhibit their widespread use. The long-term durability of concrete containing these materials must be studied in much greater detail.

Antipollution measures have stimulated interest in the recycling of residual concrete and water from washed mixers in ready-mix concrete plants, and in precast concrete operations. When used in concrete, solids in the wash water require a large amount of water because of the higher surface area. Hence, such concrete will exhibit larger drying shrinkage, increased setting time and lower strengths. This may be overcome by developing machines to separate the particles and applying certain physical and chemical treatments to the recycled materials.

DEVELOPMENT OF NEW MATERIALS

Although many building materials perform satisfactorily, some could be replaced with new materials possessing better durability characteristics. New material systems also need to be developed for use in structures incorporating new designs or requirements such as airtightness. Older buildings needing repairs or retrofitting may also require new materials or systems compatible with the older materials. New roofing materials, fast-setting cements, admixtures, sealants and composite materials (such as fibre-reinforced cements and polymer concretes and plastics) are examples of such products.

While there are several advantages in installing insulation on the outside of walls, the surface of the insulation must be protected from the detrimental influences of rain, heat and mechanical forces. One solution is to apply a coating, usually a mortar, compatible with the substrate. Several types of composite mortars containing cement, latex, fibres and other ingredients have been proposed. There have been problems in trying to evaluate these materials in the laboratory and a reliable accelerated test is required.

Several types of precast fibre-reinforced products have attracted attention in recent years because their high flexural and impact strengths offer several advantages such as post-cracking durability, controlled cracking and economy of size. Since 1960 glass fibre has been investigated as a possible alternative to other fibres in cements. While some glass-fibre composites have good resistance to alkali attack, their long-term performance and durability have not yet been fully ascertained. New formulations in glass fibre and the search for alternatives continue. One suggested material is mica of a particular aspect ratio. By adjusting the

water/cement ratio and amount of mica flake the modulus of rupture can be increased by 50-75%. One advantage in using mica flakes is their resistance to alkali attack [3].

There has been an increased interest in the production of sawdust concrete. Although lightweight sawdust concretes have been produced, shrinkage may pose problems in many instances. If these blocks have to be used with normal cement mortars differential shrinkage problems may arise.

The freeze-thaw resistance of concrete is increased by air-entrainment but it is not easy to control air content under certain conditions of mixing and placing of concrete. It has been found that by using a porous particle admixture (30% porosity and pore diameter mainly between 0.3 and 2 μm) concrete with excellent frost resistance can be made. Minerals such as vermiculite, pumice, brick powder and perlite can be used for making these porous particles [8].

DURABILITY CHARACTERISTICS

Many standard methods used to assess durability in a given service may be inadequate; materials rejected as "nondurable" have performed satisfactorily and some that have passed the tests have shown poor performance. In many instances, understanding the mechanism of deterioration and the microenvironmental factors to which the materials may be exposed under service conditions is essential for developing valid tests.

In most studies only the ambient conditions in which a material is exposed are used in artificial tests to assess performance. In the context of weathering, external factors such as temperature, moisture (precipitation and relative humidity), solar radiation, wind and pollutants are usually taken into account. However, the condition existing within the material is what determines its ability to withstand physical and chemical agents. The surface of an asphalt-covered flat roof may reach a maximum temperature of 88°C on a sunny day in summer and a black PVC panel 30 to 45°C when the ambient temperature is only 0 to 10°C [9]. Corrosion can occur at a fast rate in the atmosphere at a relative humidity of about 85% although it is often assumed that it occurs only in the presence of liquid water. Similarly, the surfaces of plastics, protective coatings and roofing membranes can begin to deteriorate when the relative humidity is high or when the surface temperature is lower than the dew point of the air, thus proving that precipitation need not be a prerequisite for the initiation of deterioration. The microenvironmental conditions play an important role in the deterioration of plastics exposed at different angles.

As already stated, some accelerated test methods for assessing durability have not proven satisfactory. One reason is the approach used for developing these tests. In accelerated weathering tests for organic materials, the procedure has been to presuppose important expo-

sure factors in a given service and incorporate as many of them as possible in a test chamber. Each factor is allotted a proportion of the exposure cycle and the test determines whether a material will fail within a certain time. However, it is much more effective to determine first the basic processes that occur in the degradation of a material and tailor the test to reproduce them [10]. Another approach is to determine the basic properties of a material that contribute the most to good service life. Studies of this nature on clear wood finishes led to the discovery that the durability of phenolic varnishes exposed naturally is related to their water absorption, water vapour permeability and, to a lesser extent, tensile strength [11]. Similar results were obtained with alkyls.

The first approach was also used in studying the fading of poly (vinyl chloride) (PVC) during exposure in Ottawa. It was found that an epoxidized soybean oil plasticizer hydrolyzed in PVC siding under hot, humid conditions in the presence of HCl arising from the vinyl resin, and migrated to the surface as a white layer. Panels exposed for 1 month to controlled changes in temperature and humidity for specified periods showed a tendency to develop such a layer [12].

TEST DEVELOPMENT

Generally, the criteria for accepting or modifying test methods for building materials are based on simplicity, immediate need, economy, research experience, available equipment and ease of measurement. However, a realistic evaluation of a material sometimes requires using complex techniques that do not conform to the above criteria. For example, a requirement that a building material should not emit more than a few parts per billion of a gas can only be determined using very sophisticated techniques.

According to the standard linear traverse test, air-entrained superplasticized concrete fails to achieve the required air content and air void spacing required for frost resistance. Nevertheless, other tests for measuring frost resistance show that such concretes have excellent durability to frost action. This would suggest that the linear traverse test, effective in measuring larger voids, is not reliable for assessing air-entrained superplasticized concrete. A recent investigation has shown that for such concretes, and perhaps for others, durability is determined by the volume of pores of size 0.3 to $2\text{ }\mu\text{m}$ [13]. Such measurements can only be carried out by realistic techniques such as mercury porosimetry or isothermal adsorption.

In the standard test for frost susceptibility of bricks, the test based on saturation coefficient values does not yield reliable results. However, a more complex test based on surface area by N_2 is capable of distinguishing poor bricks from good bricks [14]. In one experiment, it rated the values for bricks that have performed well in the field below $1.11\text{ m}^2/\text{g}$, whereas for those termed questionable or unsound, it showed values of 1.35 to

$8.25\text{ m}^2/\text{g}$. As the surface area determination needs expensive instrumentation, attempts are being made to apply simpler methods, such as the Blaine method specified for determining the surface area of cements.

When new materials, such as single-ply roofing of various types, are introduced there is usually pressure to develop standard methods to evaluate these materials and their applications. Very careful assessment of the background information available on these materials in conjunction with laboratory and field studies is required before realistic standards can be prepared [15].

In some instances techniques that can be applied for the measurement of properties of one building material may not be applicable to another material. Mercury porosimetry is a popular technique for determining porosity and pore-size distribution. It is used with success for determining these values for cement pastes but presents difficulties when applied to cement-condensed silica fume pastes. In such systems the pores are discontinuous and isolated and at high pressures some pores containing small openings are broken by the mercury. In view of this, the pore-size distribution value obtained from the pressure vs. intrusion curves will be in error [16].

Accelerated test methods should take into account the types of change that the material experiences when exposed to natural weathering. For example, the performance of sealants is determined mainly by the movement they undergo. A two-part polysulfide sealant was exposed on vises that were manually adjusted to widths corresponding to the yearly cycles that occur on a strain-cycling exposure rack simulating the movements of building joints. It was concluded that the latter test could be replaced by the one using vises so that the sealant could be evaluated relatively simply [17].

ENVIRONMENTAL POLLUTION EFFECTS

One of the major concerns of industrialized countries is the pollution of air by emissions resulting from the increased use of hydrocarbon fuels. Deleterious effluents may also originate from the raw materials used to produce building materials and other products. These pollutants, which affect some construction materials as a result of complex reactions with water vapour, acidic compounds and salts, may cause surface discoloration or deterioration of the materials to varying degrees of severity. The approximate concentrations of the five most common pollutants, accounting for about 98% of all emissions, are carbon monoxide 52%, sulfur dioxide 18%, hydrocarbons 12%, particulates 10% and nitrogen oxides 6% [9].

The concentrations of pollutants in the atmosphere and in rainwater is monitored by various agencies, but little attempt has been made to relate this information to material deterioration. It has been reported that high concentrations of locally generated industrial SO_2 are mainly responsible for the corrosion of metals [18, 19].

Large variations in SO_2 concentrations with height and season may occur and these will affect the corrosion rate. The type of building material and its surface characteristics, and the effect of orientation, shading effects and other factors interacting in a complex way, may determine how severe the effects of pollution are [20].

An area that should receive more attention is the repair and restoration of materials that have already shown signs of distress. Nondestructive techniques to analyze the surfaces of materials *in situ* need to be developed, as well as accelerated laboratory tests that reproduce the behaviour of materials exposed outdoors for long periods. Preliminary work on some nonstructural materials has shown that the accelerated tests have potential [21].

Research is also needed to control the small amounts of kiln effluents, such as hydrogen fluoride, produced during high-temperature reactions of some raw materials.

INDOOR AIR QUALITY

Decreasing air infiltration into buildings saves energy but may adversely affect air quality and pose health hazards to the occupants. Indoor air pollutants include radon and its decay products, formaldehyde and other organic contaminants, asbestos, glass fibre, silica dust and other forms of dust, ozone and solvent vapors. A few of the pollution sources are consumer products, cigarette smoke, cooking, kerosene space heaters, and building materials.

Radon and its alpha-emitting decay products contribute most of the background radiation in buildings. Soil, construction materials and groundwater are the major sources of radon. Some by-products used for making building materials may also contain radioactive elements. For example, phosphogypsum produced from sedimentary phosphate may have a radioactivity level of 25 Ci/g. Desulphogypsum is another waste material containing radioactive materials. Indoor radon concentrations are often an order of magnitude greater than those outside the building. Determining the rate of radon emanation from various sources within a building will help to establish acceptable levels in it. Also, inexpensive measuring instruments should be developed as well as strategies to eliminate or reduce unacceptable concentrations.

Another contaminant of potential concern is formaldehyde. It is emitted by urea-formaldehyde foam insulation, plywood, particle board, fabrics, cigarette smoking and indoor combustion appliances. Formaldehyde can cause throat, skin and eye irritation and respiratory disorders, depending on the sensitivity of the individuals. Effects of factors such as relative humidity, temperature, chemical composition and wind on the rate of evolution of formaldehyde and their relation to health-related problems should be examined. A joint effort by inorganic, organic, analytical and surface che-

mists, statisticians, engineers, health scientists, computer scientists, and biologists would be essential to set up pollutant standards and seek solutions to counteract or control the emissions.

MATHEMATICAL MODELLING

A mathematical model represents a system or its components in terms of a mathematical equation. A model may be simple or complex depending on the function it is to perform and the knowledge of the researcher. Models are useful for predicting the performance of materials and for bridging the gap between research and practice. There has been an increased interest in this approach in recent years. Several international organizations are presently developing mathematical models for cement hydration [22].

The durability of bituminous membranes and shingles is affected by the granules that protect the bitumen from the detrimental effects of ultraviolet radiation. The protection depends on the amount of granules initially applied (coverage) and how well the granules adhere to the bituminous surface. Mathematical calculations have been carried out based on geometrical configurations to establish 100% coverage by utilizing proper size distribution [23]. For spherical particles arranged in the hexagonal pattern, three sizes of granules in the ratio 12:4:3 cover a surface completely while for the rectangular pattern five sizes in the ratio of 12:6:3.2:2.1:1.2 are needed.

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