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Performance of Building Materials

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Building materials must serve their intended function not only when newly installed but also for some acceptable length of time. This service life may last for the life of the building or, as with paints, for only a few years before renewal.

It is common to speak of the durability of a material as if it were a basic property, measured as the length of time it will serve satisfactorily. The useful life of a material in place, however, is always related to the particular combination of environmental factors to which it is subjected, so that durability, or service life, must always be related to the particular conditions involved.

Experience with traditional materials over many years permits prediction of the performance of the same material under similar conditions. Such trial by use has provided an answer to how but not often to why materials react as they do. When new materials are to be developed or considered or when traditional materials are to be used in untried situations, the ability to predict performance may be greatly limited unless the "why" of past experience, and thus the fundamental factors involved, are understood. This is basic to the exercise of judgment in design, a combination of experience and analysis. Such an approach is also necessary in the development and interpretation of any accelerated test method designed to improve prediction of performance.

Most building materials are complex in their chemical and physical nature, as are the processes involved in their response to environmental factors. Some generalizations may be made in these respects, however, that will improve understanding of performance and provide a basis for predicting behaviour.

Properties of Materials

Chemical Nature

The chemical nature of a material is seldom meaningful to the material user or specifier because he does not understand its implications. It is its chemical nature, however, that determines the reactivity of a material to other materials and to some elements of the environment. Thus it is a dominant factor in its stability and durability. For this reason the designer needs a sense of chemistry to appreciate the basic differences in the classes and types of materials. It is especially significant that small changes in composition (even trace amounts of some substances, as with metal alloys) can have a profound influence on the resulting properties.

An appreciation of the basic constitution of the main classes of materials becomes most significant when it can be associated with certain behaviour. For example, the influence of ultraviolet radiation on organic materials can be appreciated when it is known that the organic molecule has bonds that can be broken and that other changes can be induced through the action of this radiation. This does not happen with metals or cementitious materials. These, however, have other special characteristics, as for hydrates such as gypsum plaster that are unstable at relatively moderate temperature conditions and can undergo decomposition at low relative humidity. These examples but emphasize the importance of the chemical nature of a material, providing, in the first instance, guidelines for expected behaviour or performance for a given use.

Physical and Mechanical Nature

It is customary in structural design to consider a material in terms of the practical unit in the total structure, whether it be a beam, column, or plate. The engineering properties being given in terms of the bulk material, the assumption is made that the material is homogeneous and isotropic on a scale that is significant in the proposed design. This manner of thinking about a material does not allow for an understanding of its behaviour because at this scale the factors that determine the response of the material itself cannot be appreciated. It is like considering the response of a steel bridge to a given load without being able to analyse the stress in any one member. The bridge may carry a certain load, but it will fail in time if one member is overstressed.

To understand the physical and mechanical behaviour of a material it is necessary to think in terms of a "model" of the material that will give a physical representation of the system and describe its average chemical, physical and mechanical properties. On this basis, consideration must be given to the grain, crystallite or polymer molecules, the assemblage of these into the many geometric arrangements that occur, the space or porosity around the units, and the nature and extent of the "bonds," which are the forces that hold these building blocks together.

It is useful, therefore, to think of the material on the scale of its microstructure. In considering deteriorating processes, the broad classification of porous and non-porous is useful for identifying where the effect is to be expected.

Non-Porous Materials. Non-porous materials include the large group classed as metals and ceramics. They are polycrystalline and characterized by continuous grain boundaries. Any reaction with environmental factors is initiated at the external surface, as with corrosion of metal, and the grain boundaries often provide the "weak" area along which action proceeds inward from the outer face. In most instances a surface coating will provide adequate protection against reaction with the environment if the material itself is not resistant.

Polymers represent another group of non-porous materials that are generally amorphous (non-crystalline) and chemically characterized by their large molecular size. They are formed by polymerization or joining up of simple molecules, which are either gases or volatile liquids. For example, butane (a volatile liquid) differs chemically from polyethylene only in the size of the molecule.

The chief characteristic of this group of materials is plasticity. Deformations of 100 per cent are possible before failure. This occurs partly because of their amorphous nature, where large chain-like organic molecules are randomly oriented and held together by physical forces of attraction, and partly because at normal temperature they are in a state that would correspond to near-melting temperature in metals. Polymers become more like plaster or glass when temperature is lowered.

Porous Materials. Most naturally occurring materials and those classed as cementitious materials formed by hydration or other chemical reactions of inorganic constituents are porous in the sense that they contain spaces around crystallites or grains that are interconnected.

These spaces are usually of varying size and shape, and the interconnecting channels are often extremely small and tortuous. It is of great importance to distinguish between pores that are interconnected and communicate to the outside environment of the material and those that are essentially isolated "bubbles" inside a matrix of the material. The reasons for this are obvious: when the pores communicate to the outside, the surface area of the material is potentially the total surface of the pore space. A non-porous material 1 cu cm in volume will have 6 cm^2 of surface. The same volume of a porous material, e.g. gypsum plaster, when made up of particles of 10μ (0.01 mm) will have a surface of 6000 cm^2 (0.6 m^2) and, if the particles are 0.1μ diameter, the surface will be 60 m^2 (0.015 acre), e.g. cement paste.

Because reactions with environment begin at the surface a material with a greater surface area is liable to attack in proportion to its increased surface area.

Total porosity is the most important parameter when considering the microstructure. It has a great effect upon strength (discussed in relation to concrete in **CBD 15**) but, more important, it provides the "reservoir" for water which can undergo freezing with corresponding dilation, or a medium for dissolution of constituents for reactions with foreign substances from the atmosphere. It is not generally appreciated that the total porosity of many practical materials is so large. Normal plaster can have a porosity over 50 per cent by volume, and concrete can be equally porous in extreme cases.

Environmental Factors

Environment can be defined as the combined effect of a number of factors that interact with the material: temperature, moisture, solar radiation, foreign matter. Although these can often be measured separately and recorded quantitatively against basic standards, their significance to the performance of a material lies in the degree of their interaction with the material. The material responds to actual temperature and its variation inside the material. This may be quite different from the temperature of the air surrounding the material because of thermal lag and radiant heat loss or gain.

Moisture content, its variation through the material, and the range in the cycle from wet to dry or the reverse, will depend on a combination of factors including rainfall, wind, humidity, and other factors pertaining to the physical nature of the material, as well as to its location with respect to other components. Again, what matters in determining performance is the moisture content and its change in the material.

The ultraviolet component of solar radiation is important in the deterioration process of organic materials only in the degree to which the chemical nature of the material permits interaction and the relative amount of radiation that reaches it. This is determined by its orientation and location in the structure.

In the context of this Digest, foreign matter is defined as any substance or agent that comes in direct contact with a given material. It may be a gas, liquid, bacteria, fungus, animal or insect, or even another component of the same structure. A material may interact with its neighbour or with a constituent from the environment to produce a change in properties.

Because environmental factors act in combinations and go through daily and seasonal cycles, imposing constantly changing conditions, the result is a most complex set of variables that controls the successive or simultaneous chemical and physical processes responsible for changes in materials. This makes identification of the processes or factors responsible for failure extremely difficult.

Chemical and Physical Processes

Aging

Many materials undergo slow chemical and physical changes referred to as aging (not to be confused with curing) for some period after their manufacture. These changes may involve the completion of some of the reactions of forming or the reverse reactions when the material tries to adjust to conditions of storage or service. Such changes are often difficult to differentiate from changes involving weathering processes.

Many organic materials such as plastics and sealants undergo aging. Plastic floor tile often shrinks for a period after manufacture; and freshly fired brick or clay tile also may undergo dimensional changes in storage while adjusting to new conditions of moisture content.

Efflorescence and Crystallization of Soluble Salts

Basically, this process involves soluble salts from either the materials themselves or pollution sources in the atmosphere. The salts are dissolved and moved by the free water in the pores of the material to the surface where the water evaporates, leaving the salts in the form of a stain called efflorescence. When evaporation occurs in cracks or cavities in the material the result may be an expansive force that tends to separate the neighbouring materials. Because of this action of crystallizing salts the process has often been linked with frost action, where water in the pores of material crystallizes to ice, also with an expansive force. Any given failure in a material, therefore, cannot be simply diagnosed as caused by one or the other of these processes.

Although it is known that the process of crystallization involves soluble salts and water in the material, the mechanism of the action in the pores of the material is not understood well enough to permit prediction by suitable tests and enable adequate control. The best safeguard is to prevent entry of water into the material.

Frost Action

The freezing of water in porous materials is perhaps the most important cause of weathering of materials in Canada. Frost failure occurs only in materials that are frequently frozen when very wet, and much effort has been made to establish a criterion for the degree of wetness at which a material becomes susceptible to frost action. Various combinations of structural parameters such as saturation coefficient and porosity have been found helpful in assessing frost-resistance of some materials, especially stone, but no single parameter or combination of parameters has yet been found that will accurately indicate the frost-resistance of all porous building materials. This emphasizes present lack of understanding of this process.

It is known that materials having high porosity and small pores are generally more susceptible; and that alternate cycles of freezing and thawing and high rates of freezing contribute to rapid destruction by frost action in a material close to or at saturation.

Wetting and Drying Movement and Thermal Movement

It is a common experience that materials move with changes in moisture content and changes in temperature. If the material in a structure is homogeneous and changes in moisture and temperature occur more or less uniformly throughout the bulk of the material, very large movements can be accommodated without failure. Changes in moisture content and temperature involving gradients that result in stresses within the material, however, can cause cracking as is the case with drying shrinkage of concrete. Cracks may also form because of stresses resulting from combining dissimilar materials.

Although cracks caused by moisture and thermal movements do not always cause failure by themselves, they often serve as openings through which more rain can enter the structure, making it easy for other processes of salt crystallization and frost action to take place.

Chemical Attack

Changes in materials, both beneficial and destructive, can occur as a result of chemical processes. These can involve interaction with water or foreign matter from the environment or with neighbouring materials. Corrosion of metals, alkali-aggregate reactions in concrete, sulphate attack on concrete, weathering of stone and mortar by the action of rain water acidified by the sulphur gases in the air, and photochemical reactions involving ultraviolet light from sunlight and organic materials are but a few of the more common reactions.

For chemical reaction to take place the "ingredients" must come into contact, usually through a common medium such as water. Thus, if materials are kept dry much of the chemical attack can be stopped. Reactions usually occur at the surface (in porous materials this includes the internal surface), so that a highly porous stone is much more subject to attack by sulphur gases than less porous stone. Where porosity involves only very small channels, as with dense concrete, the rate of transfer of water and solution may be so slow that for practical purposes the internal surface is not available for reaction with external agents.

Temperature also is an important factor. A useful guide is that the reaction rate doubles with every 10-degree Centigrade rise in temperature.

Chemical attack, in the first place, alters the properties of the parent material, but in the process it also produces products that may occupy a larger volume. The result is a dilating pressure (a physically destructive process similar to frost action) that may initiate cracks in the material. These cracks will accelerate the progress of other destructive processes so that in the end the material may deteriorate by a number of chemical and physical processes. It is this aspect that makes analysis of failure very difficult.

Performance and Testing

Exact prediction of performance requires a complete understanding of material properties, the processes involved in the interaction of the material with its environment, and the environmental factors to which it will be subjected. The only complete test of performance is trial by use. Prediction will always be limited by lack of complete knowledge; trial by use will be limited by time and inability to extrapolate to new conditions. Test methods can be used to supplement knowledge and experience in predicting performance.

Some test methods depend on empirically derived relations between observed behaviour and some easily measured physical property; others subject the material to environmental conditions simulating those to be expected in practice. The development of better test methods and their proper application in practice can only come about through better understanding of materials and their performance. Such understanding is also prerequisite to the proper and necessary evaluation of past experience.