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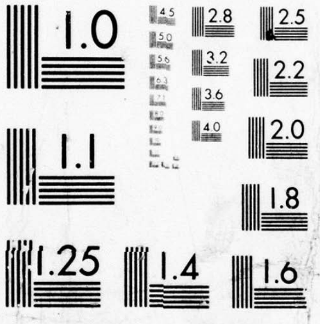

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CONCRETE FOR EARTH-COVERED STRUCTURES.

by

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U. S. Army Engineer Waterways Experiment Station
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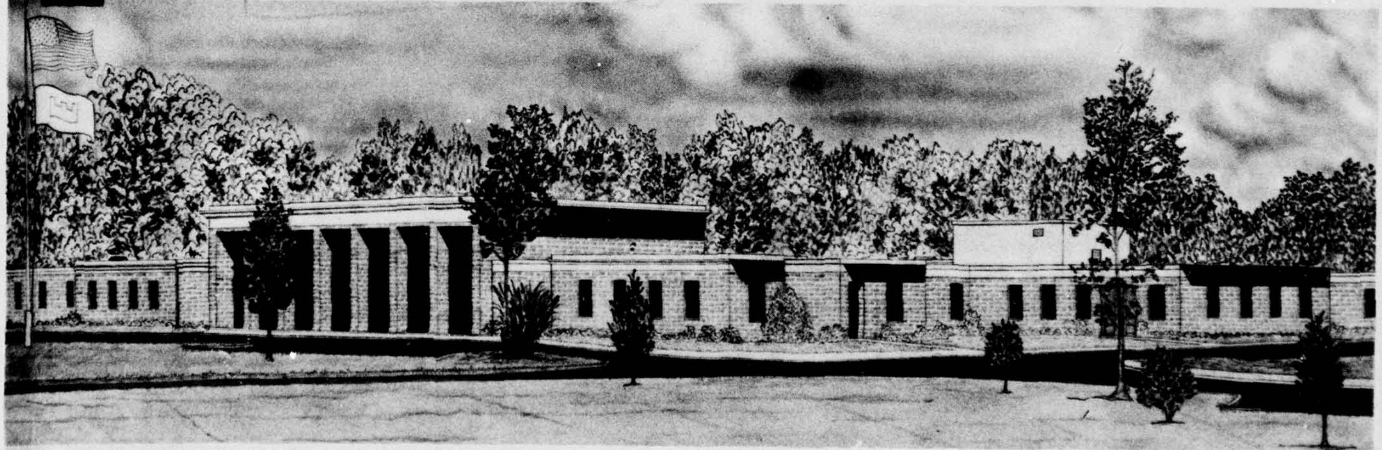

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Low permeability to water is a primary consideration in the design and construction of earth-covered concrete structures. Factors affecting the permeability of concrete are generally classified into three groups: (1) constituent materials, (2) methods of concrete preparation; and (3) subsequent treatment of the concrete. Each group of factors is examined in this paper and recommendations are made on how to obtain concrete that is virtually impermeable.

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CONT

Also, some specialized concretes with potential applications in earth-covered structures are discussed briefly. These include polymer-impregnated, polymer, and fiber-reinforced concretes and ferro-cement.

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PREFACE

This paper was prepared at the invitation of Dr. Jason Shih, Louisiana State University, for presentation at the conference "Alternatives in Habitat: The Use of Earth-Covered Settlements." This conference, sponsored by the US Department of Energy, was held 17-20 May 1978 in Fort Worth, Texas.

Funds for the publication of this paper were provided from those made available for operation of the Concrete Technology Information Analysis Center (CTIAC). This is CTIAC Report No. 34. The paper was prepared by James E. McDonald, Chief, Structures Branch, and Dr. Tony C. Liu, Research Structural Engineer, Structures Branch, Engineering Mechanics Division (EMD), Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES). The paper was prepared under the general supervision of Messrs. Bryant Mather, Acting Chief, SL, and J. M. Scanlon, Chief, EMD, SL.

The Commander and Director of WES during the preparation and publication of this paper was COL J. L. Cannon, CE. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
pounds (force) per square inch	0.006894757	megapascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$

CONCRETE FOR EARTH-COVERED STRUCTURES

INTRODUCTION

Portland cement and concrete are made and sold because they can serve some needs of mankind more economically and more satisfactorily than competitive products. There is, however, virtually no end product in which cement is used that could not be replaced by one containing no cement, if some other more economical and more satisfactory material were available. Concrete dams, concrete buildings, concrete roads, concrete wharves, concrete tanks, concrete bridges exist not because there is no other way to provide these structures, but because an engineering and economic conclusion was reached that concrete was the most economical and satisfactory material to employ.[1] Earth-covered concrete structures are no exception.

Concrete is a composite of at least three and usually four distinct categories of components: cement, aggregates, and water, plus one or more admixtures. These components can be proportioned to produce concretes with a very wide range in properties. Concrete can be of nearly any color from white to black. The density of concrete can vary over a wide range, from as low as 20 lb/cu ft*to more than 350 lb/cu ft. Concrete can be so soft it can be excavated by a teaspoon or a fingernail or it can be so hard that diamond-tipped tools cut it only with difficulty. It can be produced so that under quite small loads, less than 100 psi, it will deform so as to be reduced in volume to half, or it can resist very large loads --

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*A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

20,000 psi or more-- with little deformation. It can be produced so it will be destroyed at relatively low temperatures or be highly refractory. It can be made to be a rather good electrical or heat conductor or a very effective electrical insulator or thermal insulator. It can be provided with great chemical resistance to many varieties of aggressive influences or it can be quickly destroyed by these same influences. It can be highly permeable or nearly impermeable. It can be provided with surfaces of great smoothness or great roughness; and this catalog could be extended.

As evidenced by the above, much has been learned about the levels of properties concretes can be provided with. We are making progress in learning which properties are relevant to performance of different concretes for different uses in different environments. We have a long way to go to learn precisely what levels of what relevant properties are critical to concrete for each particular use in each particular environment.

Strength of concrete is commonly considered its most valuable property, although in many practical cases other characteristics, such as durability and impermeability, may in fact be more important. Obviously, low permeability to water is a primary consideration in the design and construction of earth-covered concrete structures. The terms "waterproofing" and "dampproofing" have frequently been used incorrectly: "dampproofing" to refer to methods of making concrete of low permeability to water vapor or to liquid water under low pressure, while "waterproofing" has been used to refer to any method of making concrete of low permeability to liquid water that may be under high pressure.[2] In either case, permeability of the concrete is of primary interest, and all terms ending in "-proof" should be avoided entirely.

PERMEABILITY OF CONCRETE

The permeability of concrete to water can be determined in the laboratory by means of a simple test (CRD-C 48-73).[3] The sides of a cylindrical test specimen are sealed and water under 200-psi (1.38 MPa) pressure is applied to the top surface only. Observations of volume of flow through the specimen are continued until the flow becomes essentially constant, normally after 14 to 20 days. The permeability is expressed as a coefficient of permeability based upon an application of Darcy's law for unidirectional flow at constant head

$$\frac{Q}{A} = k \frac{H}{L}$$

where Q = rate of flow, cubic metres/sec

A = cross-sectional area of test specimen, square metres

$\frac{H}{L}$ = ratio of head of water to length of test specimen

k = coefficient of permeability, metres/sec

The permeability test is very sensitive to minor defects or nonhomogenous conditions in the concrete. Such conditions that would have no appreciable effect on compressive strength influence the leakage through the specimen to a marked degree.[4]

Fundamentally, the flow of water through concrete is similar to flow through any porous body. However, the permeability of concrete is not a simple function of its porosity, but depends also on the size, distribution, and continuity of its pores. Glanville[5] classified the several factors affecting the permeability of concrete (Figure 1) into three groups, (1) constituent materials, (2) methods of concrete preparation, and (3) subsequent treatment of the concrete.

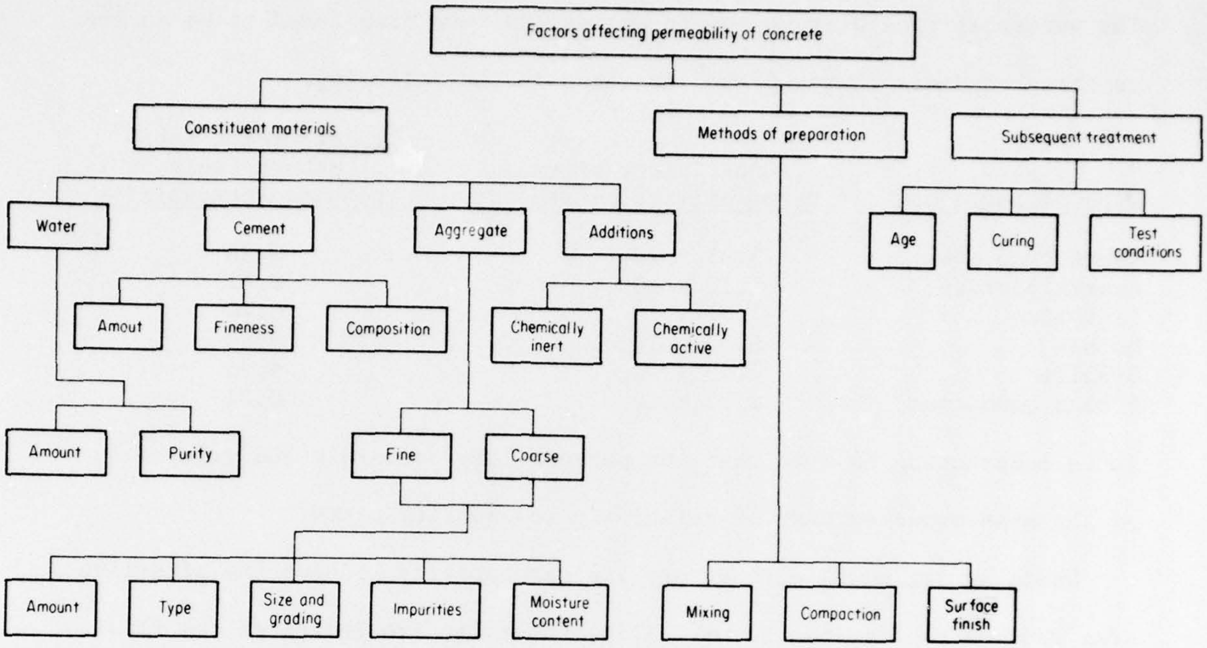

Figure 1. Factors affecting permeability of concrete (from Reference 5).

Effect of Cement

For the same water-cement ratio the ultimate porosity of paste made with coarse-ground cement is likely to be higher than that made with fine-ground cement.[6] The chemical composition of cement affects permeability in so far as it influences the rate of hydration, but the ultimate permeability is unaffected.[6]

Effect of Aggregate

Concrete contains approximately 75 percent aggregate by volume, and the aggregate can contribute significantly to the properties of the concrete. The porosities of common aggregates range from near 0 to as much as 20 percent by volume. These pores are larger than the gel pores in paste, frequently at least the size of the largest paste capillary pores.[7] The permeabilities of some common aggregates have been found to be as low as those of dense cement paste[6] as shown in the following.

Type of Aggregate	Coefficient of Permeability, metres/sec	Water-Cement Ratio of Mature Paste of the Same Permeability
Dense trap rock	3.45×10^{-15}	0.38
Quartz diorite	1.15×10^{-14}	0.42
Limestone	1.72×10^{-14}	0.44
Marble	8.05×10^{-13}	0.66
Granite	7.48×10^{-12}	0.70
Porous sandstone	1.72×10^{-11}	0.71

It is interesting to note that the permeability of marble and granite is of the same order as that of relatively low quality paste.

Using an aggregate with a very low permeability reduces the effective area over which flow can occur. Also, the effective length of the flow path becomes considerably longer since the flow path has to go around the aggregate particles. Obviously a well-graded aggregate is important in developing concrete with low permeability. For a given water-cement ratio permeability increases with increasing maximum size aggregate (Figure 2), probably because of the water voids developed underneath the larger aggregates.[8] However, the influence of the aggregate content in the mixture is generally small and, since the aggregate particles are enveloped by the cement paste, in fully consolidated concrete it is the permeability of the paste that has the greatest effect on the permeability of the concrete.[9]

Effect of Cement Paste

The water-filled space in a freshly mixed cement paste represents space available for the formation of cement hydration products. As hydration progresses, the volume of this space is continually reduced by the

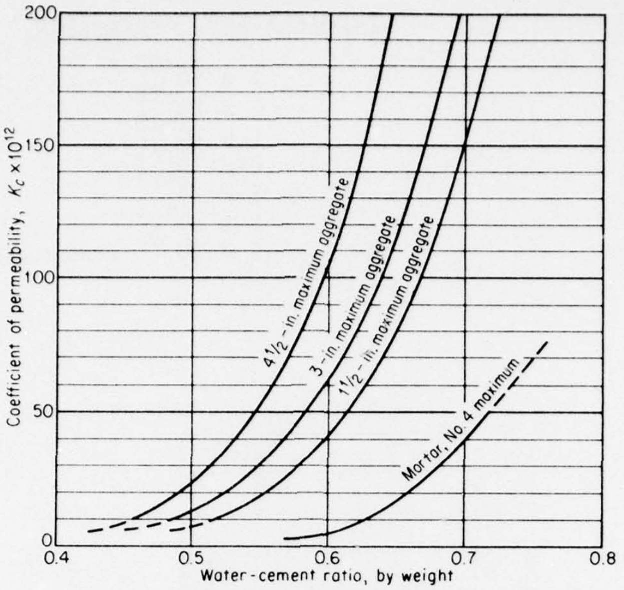

Figure 2. Effect of maximum size aggregate on permeability (from Reference 8).

precipitation of hydration product (gel). At any time, that portion of the original water space which has not been filled with gel constitutes the capillary pores of the paste. The gel itself contains many very small pores. These gel pores are much smaller than the capillary pores. Gel pores constitute about 28 percent of the paste volume and capillary pores between 0 and 40 percent, depending on the water-cement ratio and the degree of hydration.[9] As a whole cement paste is 20 to 100 times more permeable than the gel itself,[10] therefore, it follows that the permeability of cement paste is controlled by the capillary porosity of the paste (Figure 3).

Permeability decreases rapidly with the progress of hydration as shown in the following, because the gross volume of gel is approximately twice the volume of the unhydrated cement.

Age, days	Coefficient of Permeability, metres/sec
Fresh	2×10^{-6}
5	4×10^{-10}
6	1×10^{-10}
8	4×10^{-11}
13	5×10^{-12}
24	1×10^{-12}
Ultimate	6×10^{-13} (calculated)

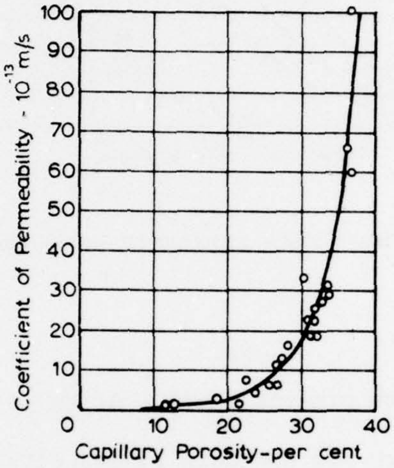

Figure 3. Effect of capillary porosity on permeability (from Reference 10).

For a given degree of hydration, permeability decreases with a reduction in water-cement ratic (Figure 4).

Effect of Admixtures

The entrainment of air would be expected to increase the permeability of concrete. However, since air entrainment reduces segregation and bleeding and improves workability, thus permitting the use of a lower water-cement ratio, the net effect of air entrainment is not necessarily adverse. In

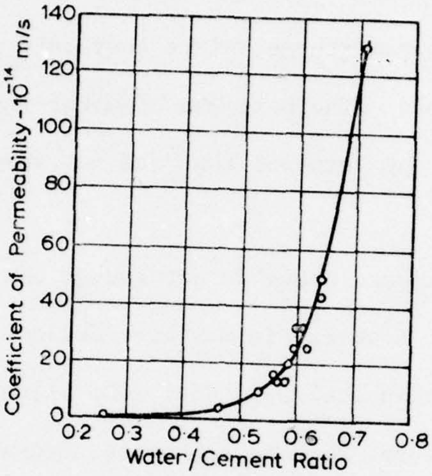

Figure 4. Effects of water-cement ratio of mature cement pastes on permeability (from Reference 6).

earth-covered structures which are not exposed to freezing and thawing the use of entrained air may be optional and related to the use of water-reducing admixtures to achieve the desired workability at a low water-cement ratio.

Permeability-reducing admixtures are substances that are incorporated in the concrete mixture to render the hardened concrete less permeable. Many of these admixtures are lime soaps which form hydrophobic or water-repellent linings in the pores of the concrete. Water-repellent compounds consist of soaps, butyl stearate, and certain petroleum products.[11-17] The soaps comprise salts of fatty acids, usually calcium or ammonium stearate or oleate. With the exception of butyl stearate, they cause entrainment of air during mixing. Among petroleum products are mineral oil, asphalt emulsions, and certain cut-back asphalts. Test results show that water-repellent compounds reduce the rate of penetration of moisture into the micropores of dry concrete, but do not reduce the coefficient of permeability of saturated concrete.[11] Therefore, they should probably not be called permeability-reducing admixtures, since they only reduce the rate at which saturation is approached. The best use of water-repellent compounds appears to be in walls, slabs, and sections that are not subjected to tension or hydrostatic pressure.

Admixtures of the kind discussed above do not reduce the water permeability of saturated concrete. However, in mixtures deficient in fines (particularly aggregate finer than the 75-μm (No. 200) sieve) addition of a finely divided mineral admixture, such as bentonite, hydrated lime, or a pozzolan, improves workability, reduces the rate and amount of bleeding and, therefore, reduces permeability and porosity.

If pozzolanic materials are used for this purpose, they should be of suitable quality. Many pozzolanic materials, due to size, shape, surface texture, and grading of their particles, cause an increase in water requirement of concrete in which they are used as compared to that of comparable concrete without pozzolan. When water content is increased, the absorption and permeability of the concrete may be increased.

The reduction of total water content by means of a water-reducing admixture should reduce the total porosity slightly,[18] but there are no adequate data to demonstrate that permeability is thereby reduced materially.

Accelerating admixtures such as calcium chloride increase the average rate of hydration and thereby reduce the length of time required for a concrete mixture to attain a given fraction of its ultimate degree of impermeability. However, any advantage attained this way is likely to be temporary since, if conditions are such that water is being transmitted through concrete, they are also conducive to continued hydration of cement.[11]

The general conclusion seems to be that permeability-reducing admixtures are not dependable to effect any important reduction in water penetration of concrete so-treated. These admixtures should not be expected to offset poor workmanship or improper curing. They will not be effective if the concrete cracks.

Effect of Placing and Curing

Probably the majority of leaks in concrete structures are due either (1) to defects such as cracks in the structure or (2) to void spaces in the concrete caused by honeycombing or segregation of the constituent materials rather than to inherent porosity of the cement paste or aggregate.[4] The latter can be avoided through appropriate attention to handling, placing, and consolidation of properly proportioned concrete. The effect of vibratory compaction in reducing the permeability of concrete with 2- to 4-in. slump is shown in Figure 5.

As previously shown, permeability decreases rapidly with the progress of hydration, therefore, the need for proper curing is obvious. The effect of moist curing on permeability is shown in Figure 6. Permeability of steam-cured concrete is generally higher than that of fog-cured concrete.[20] Supplemental fog curing of concrete initially steam-cured may be required to achieve an acceptably low permeability (Figure 7).

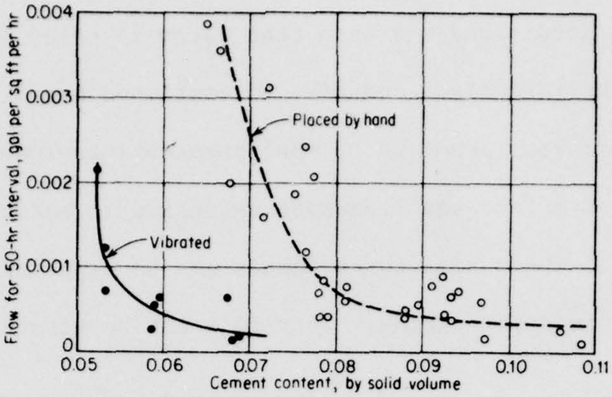

Figure 5. Permeability of hand-placed and vibrated concrete (from Reference 4).

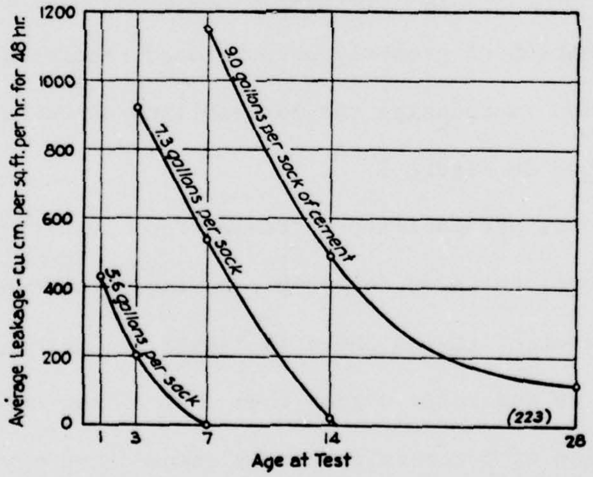

Figure 6. Effect of curing on permeability (from Reference 19).

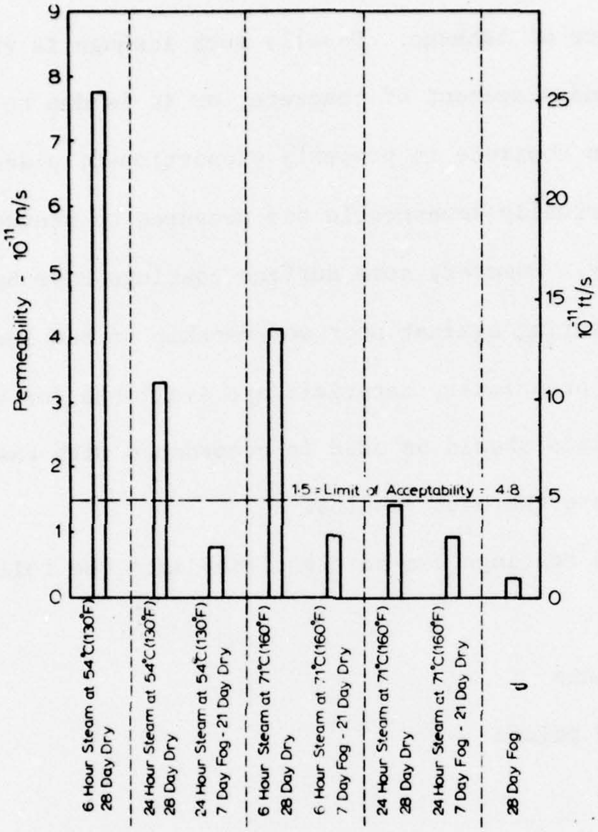

Figure 7. Permeability of steam-cured concrete (from Reference 20).

In general, any factor tending to improve the strength of concrete will have a beneficial effect on its permeability. One exception to this statement is drying the cement paste which increases its permeability, probably because shrinkage may rupture some of the gel between the capillaries and thus open new passages to the water.[6]

CONCRETE COATINGS

Some concrete underground structures, retaining walls, and other structures show evidence of leakage. Usually such leakage is the result of faulty production and placement of concrete, or it is due to cracks in the structure. When concrete is properly proportioned, placed, and cured, it should be virtually impermeable and measures to prevent leakage should not be necessary. However, some surface coatings have been advocated as a means of insuring against poor workmanship or bad luck.

A large variety of proprietary materials are available for use as coatings. These materials should be used in accordance with the manufacturer's recommendations to secure the best results.

In general, surface coatings can be classified into the following categories.

1. Cement-base paints
2. Solvent-thinned paints
3. Emulsion paints
4. Bituminous coatings
5. Silicones
6. Epoxy and related coatings
7. Miscellaneous coatings

A comprehensive review of the general subject of coatings to reduce leakage through concrete can be found in References 21 through 28.

In general, surface coating materials are usually more effective if they are applied on the face of the concrete in contact with the soil or water. Lasting effects cannot usually be expected if the coatings are applied so that pressure will be developed behind them, as may be the case on the interior surface of an underground building wall.

Test results[21, 22] have shown that properly applied and cured portland-cement mortars, bituminous materials, heavy petroleum distillates dissolved in volatile solvents, linseed oil, and epoxy and related coatings are effective in decreasing permeability of concrete. Among these materials, bituminous coatings are probably most widely used on underground concrete structures and basement walls, where appearance is not a factor.[23] The heaviest duty bituminous coating is a membrane formed by mopping of asphalt or coal-tar into some kinds of bituminous-impregnated fabric, such as burlap, cotton fabric, woven glass, and felts. A properly constructed, intact bituminous membrane is probably the best coating presently available for reducing leakage in underground concrete structures.

SPECIALIZED CONCRETES

Several broad varieties of specialized concretes have been developed for particular applications. Some of these concretes with potential application in earth-covered structures are discussed briefly in the following.

Polymer-Impregnated Concrete. Polymer-impregnated concrete (PIC) is portland-cement concrete impregnated with a monomer which is subsequently polymerized, either by ionizing radiation or thermal treatment. At ambient temperature and pressure, monomers can be either gases (e.g., vinyl chloride), liquids (e.g., methyl methacrylate), or solids (e.g., acrylamide). Liquid monomers are most adaptable to impregnation of precast concrete, although gaseous monomers have been used.[29,30] The PIC may be extremely strong, impermeable, very resistant to freezing and thawing and salt-water attack, and highly abrasion-resistant (Tables 1 through 3).

Many applications for use of PIC have been reported in the U.S. and overseas.[31] They include repair of bridge decks and stilling basins, tunnel support and lining systems, precast pipes, underground mine support systems, desalination plants, offshore drilling and production platforms, concrete ships and vessels, curbstones, and plumbing fixtures. The PIC, because of its high strength, low permeability, and good durability, holds great promise for precast elements for underground concrete structures.

Polymer Concrete. Polymer concrete (PC) is a composite material consisting of a polymer matrix and particulate fillers, prepared by the integral mixing of a polymerizable material (e.g. monomer or resin) and aggregate. Polymerization is usually obtained through a catalyst-promoter system without the introduction of radiation or thermal energy.[31] Various polyesters, epoxies, furans, and poly methyl methacrylate have been used as the matrix of PC. Among the unique properties of polymer concretes are their high tensile, shear, bond, and compressive strengths, high corrosion resistance, rapid strength development, excellent insulation properties, etc.[32] The permeability of a properly proportioned and made PC approaches zero.

Polymer concrete has been used for joining, repairing, lining, coating, and binding portland-cement concrete and for special applications where certain characteristics are needed (i.e., chemical resistance).[32] Because of its high material and handling cost, PC is not expected to be a replacement for portland-cement concrete. However, the PC has a potential application for a composite construction using a PC layer in the exterior faces of an underground concrete structure. This would reduce permeability, increase the flexural strength, and improve the corrosion protection for the reinforcement in the underground concrete structures.

Ferro-cement. Ferro-cement consists of layers of wire mesh, each coated with a thin layer of hydraulic cement mortar placed by hand or by shotcrete. Ferro-cement was developed and used by Joseph Lambot in 1848, for a small row boat.[34] Since then, many small boats and river craft have been built using ferro-cement. The durability and watertightness of these vessels are found to be excellent.[35] Ferro-cement is essentially crack free, because of the high steel percentage (about 6 percent) and good distribution of reinforcement.

Ferro-cement fabrication is an effective way of obtaining strength through form with unlimited possibilities of application to new designs of spatial, reticular, and lamella-type framework, including an underground dune dwelling.[36]

Fiber-Reinforced Concrete. Fiber-reinforced concrete is defined as concrete made of hydraulic cement containing fine or fine and coarse aggregate and discontinuous, discrete fibers.[37] Many different types of materials have been used as reinforcing fibers, with the most common being steel, glass, polymeric fibers, and asbestos. Other fibers such as mineral wool and vegetable fibers have also been used.[33]

The applications of fiber-reinforced concrete will depend on the ingenuity of designers and builders in taking advantage of the static and dynamic tensile strength, energy absorbing characteristics, and fatigue strength. Present applications of steel fiber-reinforced concrete have been in the areas of pavements, overlays, patching, refractories, concrete armor for jetties, and mine tunnel lining.[37] Isotropic strength properties obtained by the uniform dispersion of fibers throughout the volume of the concrete will permit thinner flat and curved plate structural elements. Fiber-reinforced concrete has been used for thinner and lighter wall units for housing and school buildings.[38,39] Fiber-reinforced concrete has a potential application for underground buildings to take advantage of increased strength, reduced cracking, and thickness reduction.

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Table 1

Typical Mechanical Properties of PIC[5]

Polymer	Polymer Loading, wt %	Strength (psi) Compressive	Strength (psi) Tensile	Strength (psi) Flexural	Modulus 10^6 psi Elastic	Modulus 10^6 psi Flexural
Unimpregnated	0	4,950	335	630	2.7	3.0
MMA	4.6-6.7	20,250	1,630	2,640	6.3	6.2
MMA + 10% TMPTMA	5.5-7.6	21,590	1,510	2,220	6.1	6.1
Styrene	4.2-6.0	14,140	1,100	2,300	6.3	6.3
Acrylonitrile	3.2-6.0	14,140	1,040	1,470	5.9	4.5
Chlorostyrene	4.9-6.9	16,090	1,120	2,380	5.6	6.3
10% Polyester + 90% styrene	6.3-7.4	20,500	1,500	3,300	6.5	6.4
Vinyl chloride[a]	3.0-5.0	10,240	675	--	4.2	--
Vinylidene chloride[a]	1.5-2.8	6,650	370	--	3.0	--
t-butyl styrene[a]	5.3-6.0	18,150	1,445	--	6.4	--
60% styrene + 40% MPTMA[a]	5.9-7.3	17,140	910	--	6.3	--

Note: Concrete dried at 221 F overnight and was radiation polymerized.
(a) Dried at 302 F overnight.

Table 2

Permeability and Absorption of PIC[5]

(Thermal-Catalytically Cured; Dried at 105C Prior to Impregnation)

Property	Control		MMA	Styrene	MMA + 10% TMPTMA	Acrylonitrile	Chlorostyrene
	Undried	Dried					
Water absorption %	6.4	6.2	0.34	0.70	0.21	5.68	1.97
Water permeability (10^{-4} ft/yr)	5.3	29	1.4	1.5	1.2	---	---

Table 3

Durability of PIC[5]

Property	Control		MMA	Styrene	MMA + 10% TMPTMA	Acrylonitrile	Chlorostyrene
	Undried	Dried					
Freeze-thaw							
No. of cycles	740	440	3,650	5,440	4,660	4,120	1,800
% wt loss	25	28	2	21	0	6	10
Sulfate attack							
No. of days	480	605	720	690	630	540	300
% expansion	0.466	0.522	0.006	0.030	0.003	0.032	0.009
Acid resistance, 15% HCl							
No. of days	105	106	805	8-5	709	623	292
% wt loss	27	26	9	12	7	12	8
Acid resistance, 15% H_2SO_4							
No. of days	49	77	119	77	--	70	77
% wt loss	35	30	26	29		33	26
Abrasion loss							
inches	0.050	0.036	0.015	0.037	0.019	0.026	--
wt loss (g)	14	7	4	6	5	6	--
Cavitation (in.) (2 hr exposure)	0.320	0.262	0.020	0.009	--	0.092	0.115

Note: Thermal-catalytically cured. Dried at 221F prior to impregnation.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

McDonald, James E
Concrete for earth-covered structures / by James E. McDonald, Tony C. Liu. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.
26 p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; C-78-15)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.
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