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High-Performance Materials and Systems Research Program

Use of Permeable Formwork in Placing and Curing Concrete

by Philip G. Malone

Prepared for Headquarters, U.S. Army Corps of Engineers

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Systems Research Program

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Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the High-Performance Materials and Systems (HPM&S) Research Program. The work was performed under Work Unit 33110, "Application of New Technology for Maintenance and Repair of Concrete Structures," for which Mr. James E. McDonald, U.S. Army Engineer Research and Development Center (ERDC) Structures Laboratory (SL), was the Principal Investigator. Mr. M. K. Lee, HQUSACE, was the HPM&S Program Monitor for this work.

Dr. Tony C. Liu was the HPM&S Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Don Dressler, HQUSACE, was the Research Area Coordinator. Mr. McDonald, ERDC SL, was the HPM&S Program Manager.

The work was performed at ERDC, and this report was prepared by Dr. Philip G. Malone, Concrete and Materials Division (CMD), SL, under the general supervision of Dr. Bryant Mather, Director, SL, and Dr. Paul F. Mlakar, Chief, CMD.

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At the time of publication of this report, Dr. Lewis E. Link was Acting Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

1 Introduction

Background

Permeable formwork is a special class of lined formwork intended to produce improvements in the strength and durability of the surface of concrete. The bracing and the liner in the formwork are engineered to resist the pressure of plastic (or fresh) concrete, but to allow trapped air and excess water to pass through and be removed during concrete placement and consolidation. The objective in using permeable formwork is to eliminate voids (bug holes) on the surface of the concrete and to increase the strength and durability of the concrete surface immediately behind the formwork.

The concept of using the formwork to remove excess water from cast concrete originated in the work of John J. Earley in the 1930's. Earley manufactured precast architectural facings using dry plaster molds that absorbed water from the concrete and produced a better surface finish on the ornamental castings than he had been able to obtain with coated forms. In 1938 the Bureau of Reclamation began an intensive program of investigation that led to the development of the first type of permeable formwork, which was referred to as absorptive form liner (Johnson 1941, Bidel and Blanks 1942).

The earliest types of absorptive form liner consisted of 12-mm-thick panels of pressed board made from ground cane, wood pulp, and similar materials. Even this relatively simple liner eliminated practically all pitting and voids in the concrete surfaces. The work done at Kentucky Dam (Johnson 1941) showed that the surfaces of concrete placed in absorptive formwork liners had less water absorption and showed reduced damage from freezing and thawing compared with concrete surfaces cast against oiled wooden forms. Concrete samples that had been cast against absorptive liners and oiled wood were tested by sandblasting. The sample cast against wood showed exposed aggregate while the sample cast against absorptive liners showed "practically no wear with the exception of a few voids." Generally the more absorbent the formwork, the lower the wear shown (Johnson 1941, pp 625-26). These early tests used a portland-cement concrete mixture with a 0.6 water-cement ratio (w/c) by mass. Although the 150-mm cubes used in this early testing did show higher unconfined compressive strength in the cubes cast with absorptive formwork (as opposed to conventional formwork), it was recognized that the absorptive effect of the mold had its major effect in producing a denser, more durable surface with a reduced number of bug holes (Johnson 1941).

In 1949, the U.S. Army Engineer Waterways Experiment Station undertook a comparative study of seven types of nonabsorbent liners and 13 absorptive liners, including fiberboard, blotter paper, fabric-covered chipboard, and woven fabrics over both steel and plywood forms. All of the lining materials, except the blotter paper, practically eliminated surface voids, increased the abrasion resistance, and decreased the moisture penetration of the concrete or mortar placed behind the liners. Subsurface voids could be detected if the surfaces were ground away. The commercially produced fiberboard form liners that were available at the time were included in the testing, and all succeeded in eliminating surface voids and increasing resistance to abrasion. The fiberboards all could be easily removed after 48 hr, leaving a clean surface (Department of the Army 1952).

From about 1960 to 1980, little work was done with absorptive or permeable formwork, primarily due to high cost, misuse, and difficulties in installation and removal. However, the technology gained renewed attention in 1985, possibly due to the escalating cost of lumber. Permeable formwork was extensively used in the Aseishi-Gawa Dam projects in Japan (Tanaka and Ikeda 1987, Wilson 1994). Most current literature refers to this technology as a textile form method (Marosszeky and Chew 1990, Marosszeky et al. 1993), silk form method (Price 1998), controlled permeability formwork (Long et al. 1994, Wilson 1994, Long and Basheer 1997) or controlled permeable formwork (Peter and Chitharanjan 1995), or permeable formwork (Price and Widdows 1991).

Permeable formwork liners have been used in a wide variety of modern structures, including the following:

a. Spillways on the Karakaya Dam on the Euphrates River in Turkey (Anonymous 1988).

b. Immersed tube units in Sydney Harbor Tunnel Project, Australia (Marosszeky et al. 1993).

c. Wash-water tank at Gifford, Lothian, UK (Anonymous 1994a).

d. Siphon section in the Weir on the River Mersey, near Warrington, UK (Anonymous 1994b).

e. Glen Shira Main Draw-Off Chamber, UK (Basheer et al. 1993).

The Japanese used permeable formwork liners on 135 construction projects from 1985 to 1987 (Reddi 1992).

Purpose and Scope

This study comprises one element of research being conducted by the U.S. Army Corps of Engineers to develop innovative materials and systems for economical and durable maintenance and repair of concrete structures.

Based on the cost of repairing the country's aging infrastructure (estimated to be in excess of $1 trillion), an explosive growth in concrete technology is occurring. Much of this emerging technology appears to be sound. However, its potential for use by the Corps needs to be evaluated and adapted as necessary before being adopted for widespread use. Without innovations in concrete technology, the Corps will be forced by decreasing resources to reduce the scope of its maintenance and repair programs, possibly jeopardizing the future operation of civil works structures.

This research focuses on the use of controlled-permeability formwork for high-strength, durable, aesthetically pleasing concrete structures.

Action of Permeable Formwork Liners

Absorptive or permeable formwork behaves as a filter that allows air and water to escape from the concrete that is directly behind the formwork. The concrete is retained by the filter medium (often a woven or nonwoven fabric); however, air, water, and materials dissolved in the water and very fine suspended solids can escape from the concrete adjacent to the formwork. The water draining through the liner contains a variety of dissolved and fine suspended materials. The liquid extracted from cement paste typically is a saturated calcium hydroxide solution with a pH in the range of 12.5 to 13.5. The fine suspended material can include cement particles, with an average size of 10 μm, and fine mineral admixtures, such as silica fume with an average size 0.1 μm (Neville 1973, Kosmatka and Panarese 1990).

The movement of the fluid components through the filter, especially when consolidating the concrete with vibrators, allows the escape of any air trapped immediately behind the formwork and drives out some of the water in the concrete adjacent to the formwork (Figure 1). The goal in using the permeable formwork is to allow air to escape and remove excess water (that is, water above the amount needed to stay at or below the specified value of water-cement ratio). A portion of the fine suspended materials, including cement particles and silica fume, will also be removed with the water. If the vibration is not excessive and the openings in the filter layer are small enough, the loss of cementitious components will not be excessive.

Examination of the concrete directly behind the formwork indicates that the movement of the water in the concrete will result in a decrease in the amount of water in the concrete (lowering the w/c), and fine cement particles from the interior concrete mass will be carried toward the filter layer (increasing the cement factor and further lowering the w/c at the concrete surface).

The general result of the fluid movement toward and through the filter layer in the formwork is that the surface of the concrete is denser and stronger and has fewer bug holes than the same concrete placed in conventional unlined formwork (Figure 2). Most investigations have shown that the influence of the filter layer changes the characteristics of the concrete for a depth of only a few tens of millimetres. The argument has been made that vibration will always result in forcing water to the surface of the concrete mass as the solid particles

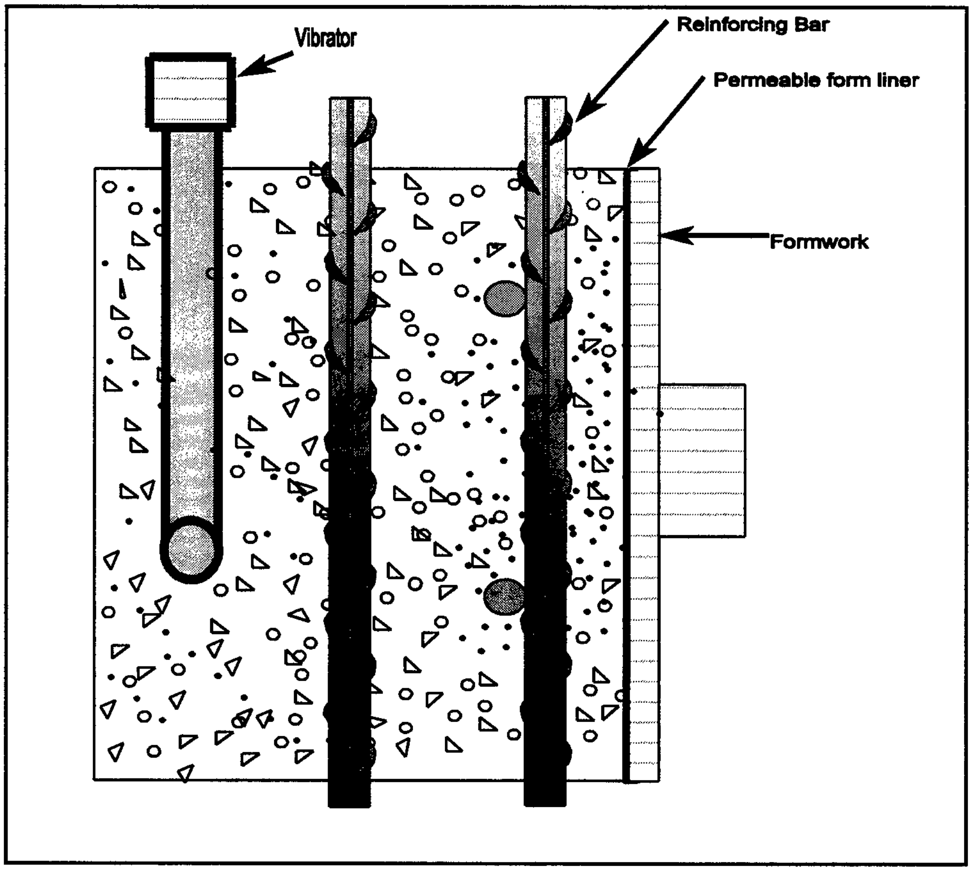

Figure 1. Action of permeable formwork (after Marosszeky et al. 1993 and Wilson 1994)

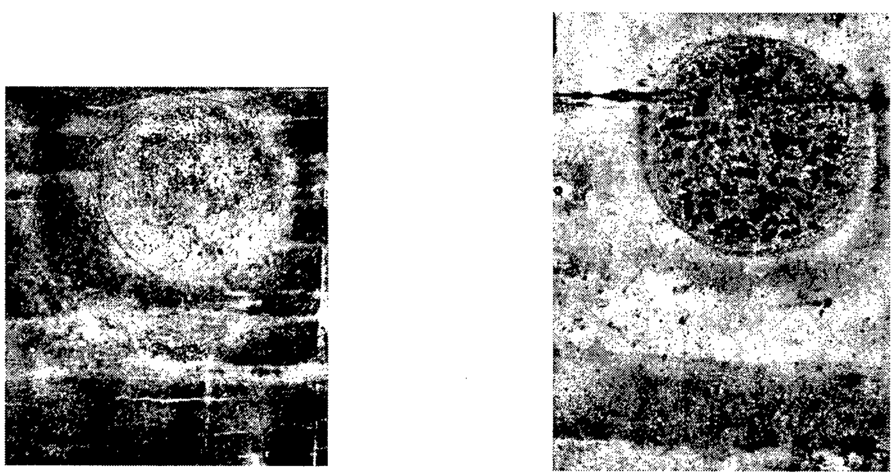

Figure 2. Samples of concrete cast against fiberboard (left) and against steel formwork (right). Note the reduced number of bug holes in the sample cast with permeable (fiberboard) formwork. Sandblasting demonstrates that the concrete cast with permeable formwork has a more abrasion-resistant surface (from Department of the Army 1952)

in the concrete are moved into more compact packing arrangements. As the particles pack together behind conventional formwork, the concrete at the concrete-formwork interface will always have more water than the concrete in the central mass of material. The higher w/c at the surface results in weaker, more permeable concrete at the surface. Filter formwork tends to correct this problem by permitting the water to pass through the concrete-formwork interface and drain out of the formwork (Reddi 1992).

2 Materials Used in Permeable Formwork

The goal in developing a fabric liner is to have a material that will pass water and air without allowing the fine cement particles to escape. The filter fabric typically must be stiff enough to lay flat over a form or must be furnished with backing materials that prevent the fabric from wrinkling and provide a path for the water to move out of the form. Additionally, the filter unit must retain some water to keep the surface of the concrete moist as it cures. The filter must also be manufactured with a surface that will minimize the tendency of the filter material to adhere to the concrete. The ideal filter materials are those that can be reused several times before they wear out. A variety of approaches to making permeable liners have been used, with varying degrees of success.

Absorptive Form Liners

The earliest filter materials were pressed boards made from wood fiber (Johnson 1941, Cron 1970). Pressed fiberboards are usually assumed to be single-use filters, and they require a coating to prevent the filters from adhering to the concrete. Generally, the absorptive boards have to be coated with a release compound such as linseed oil that will allow the boards to be pulled free from the concrete without having the boards shred during removal.

The first large-scale field tests of absorptive liners were conducted in October 1939, on the downstream face of Grand Coulee Dam. A total of 22 liner materials produced by four manufacturers were evaluated. The testing led to product improvements and better specifications. Friant Dam in California was the proving ground for absorptive liners. This project produced the specifications for manufacturing liner boards as well as practical handling and installation techniques.

As a result of early work by the Bureau of Reclamation, several manufacturers produced boards suitable for absorptive formwork. By 1941, over 20,000 m^2 of absorptive formwork had been used at Kentucky Dam. Also by this date, the Bureau of Reclamation, had developed a set of specifications for form liners based on physical properties (strength, absorption, and adaptability for field use) and on a field test that involved forming a

1- by 1.6-m slab cast on a 0.7 to 1.0 slope. A standard absorption test based on floating a 100- by 100-mm section of liner and measuring the increase in mass with time was developed. Liner materials were rated on their ability to absorb water at a specified rate.

Absorption was expressed as a curve given by an equation of the form

$$W = C \log_e T$$

where

W = mass of water absorbed by the test specimen (in grams)

C = constant referred to the absorption constant

T = time (in min)

Materials with absorption constants between 3.83 and 5.50 were acceptable. C-values below 3.83 did not remove enough water, and values above 5.50 removed more water than necessary and in some cases produced deleterious effects (Cron 1970).

In early experiments on absorptive formwork, a wide variety of candidate materials were evaluated. Burlap, muslin, fabric-covered screens and mesh, blotters, and wood pulp were among the early materials tested. Insulating wallboards (made by pressing wood, cane, and straw) were found to perform best. Care was taken to use materials that did not contain sugar or any other materials that might produce discoloration or interfere with the normal chemical reactions of the cement in the concrete. A coating of linseed oil was generally applied 48 hr before use to prevent the fibers in the wallboard from sticking to the surface of the concrete. The standard practice was to remove the treated liner within 5 days of concrete placement to prevent sticking.

Detailed instructions were developed for installing the absorptive liners, including the sizes and spacings of the nails or screws used to attach the liner to the sheathing in the formwork. Shims were developed to assist the installers in setting the proper spacing between adjacent sheets to ensure that the liner panels did not bulge when the moisture from the concrete caused them to swell.

Liner boards were furnished in standard sizes. Panels that were 12 mm thick, 1.3 m wide, and 2.6 m long were typical, although panels as long as 5.2 m were available. Special enclosures for storing the liner boards on the construction site and techniques for lifting and moving board in water-repellent bundles were developed. (Typically, a bundle consisted of six boards.) Discussions of the best formulations for concrete to be used with the panels and suggestions for using vibrators to consolidate the concrete were available. Recommendations for drying the boards if they became wet and wetting them if they were too dry were provided in specifications of construction techniques (Johnson 1941).

The Bureau of Reclamation pioneered the use of absorptive liner boards, although liner boards were investigated or used by all of the major construction agencies, including the Tennessee Valley Authority, U.S. Army Corps of Engineers, and Wyoming State Highway Department. In addition to the use of the liner boards in hydraulic structures (Friant and Kentucky Dams), other structures such as the Los Angeles Railway Terminal Building used this technology. The use of liner boards is thought to have helped the Terminal Building resist the corrosive effects of locomotive smoke. The use of absorptive form liner boards was a mature technology by 1942.

Fabric-Covered Absorptive Form Liners

An improved absorptive panel was developed in 1943. The new absorptive mold lining consisted of a single woven fabric or pressed fiber laminate (such as latex-bonded paper fiber) that was attached to a fiberboard or chipboard using a latex cement (U.S. Patent Office 1943). The filter layer was specified as being made from a fibrous water-absorbent textile such as cotton, linen, hemp, jute, or paper fiber. One example given for a filter layer was an 80- by 80-threadcount cotton sheeting. The absorptive backing board was specified as any fibrous board capable of absorbing not less than 0.24 L of water per square metre. The best selections of absorbent materials were considered to be those with an absorptive capacity of 0.48 to 1.92 L of water per square metre. The maximum absorptive capacity should be reached in 6 hr. The example given used a "60 gauge" pressed fiberboard. The absorptive panel and the filter layer were bonded together with a thin, discontinuous layer of latex cement.

Investigations undertaken on the absorptive liner showed that at the end of 3 hr the liner has absorbed the maximum amount of water (almost 2.0 L/m^2). After an additional 3 hr, the concrete surface started resorbing the water from the liner. After 18 hr the water content of the lining had dropped to 0.96 L/m^2, and at the end of 72 hr the water content of the liner dropped to 0.68 L/m^2.

Investigations were undertaken on the effectiveness of the fabric-covered absorptive liners by examining the resistance of test cubes prepared with the liner to surface abrasion and the amount of water that was absorbed by slices of concrete made at increasing distances from the surface of the concrete. The abrasion resistance was higher in the cubes cast against the fabric-covered absorptive liner and the water absorption was lower. Based on the water absorption experiments, the effects of the absorptive liner were thought to be detectable even in concrete 50 mm below the surface.

Woven Fabric Form Liners

Woven fabric form liners were used as early as the 1960's in the Netherlands for the placement of piles or piers underwater. The Japanese pioneered the use of woven fabric form liners in flat, vertical, and inclined forms around 1985 (Reddi 1992). The initial efforts involved attaching fabric to perforated metal forms. Improvements followed with a two-layered, cloth-faced form being introduced in 1988 (U.S. Patent Office 1988) and form work with a double-woven fabric appearing in 1989 (U.S. Patent Office 1989).

The fabric coverings for the formwork are generally woven from polyamide, polyester, or polypropylene fibers that will not degrade in the alkaline solution from the concrete. Fabrics are typically woven with 700 to 1,000 yarns/m in both directions using 1,000 to 2,000 denier thread. A denier is the number of 0.05-g units in 450 m of thread. This weave has been found to be sufficiently fine to retain cement particles and prevent any loss in strength of the concrete surface. Even with this fine weave, the fabric still has a permeability to water of 9.5×10^{3} cm/sec or greater.

A single layer of fabric mounted on a frame has drawbacks in that, while the water may pass through the fabric initially, there is no immediate path for the water out of the formwork. Holes can be drilled in the panels of the formwork, but closely spaced holes can weaken the formwork panels. A more practical approach is to put a more coarsely woven fabric layer (470 yarns/m), which can promote drainage, behind a finely woven layer (700 to 1,000 yarns/m) that acts as a filter. The two-layered structure can be either two fabric layers or a single layer of double-woven fabric (Figure 3). Where two separate fabric layers are used, the layers are typically stitched through vertically at 2-mm intervals. The Japanese have also developed a form liner that is a woven polyester filter fabric bonded to a nonwoven (spun-bonded) polyester drainage fabric.

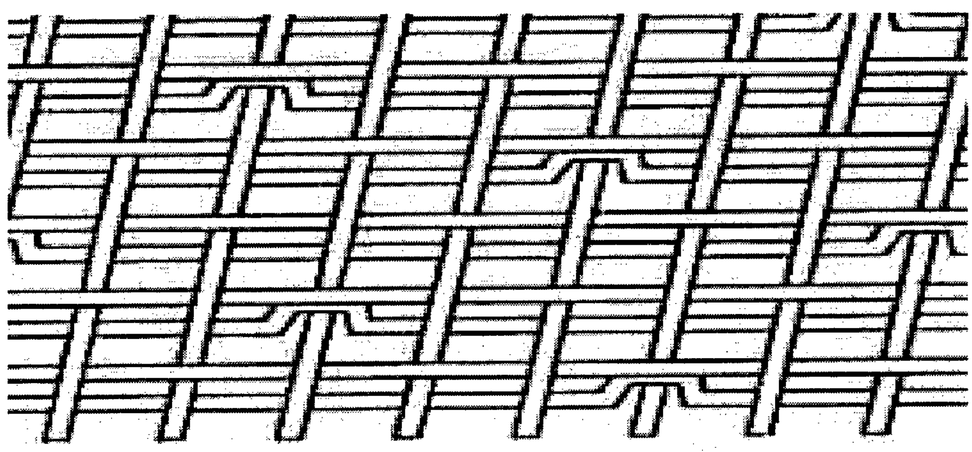

Figure 3. Diagram of double-woven fabric showing the second fabric layer. The weave of the two layers can be varied to allow a finer surface layer to act as a filter while a coarser lower layer provides drainage (from U.S. Patent Office 1989)

The Japanese specifications for a double-woven fabric form liner requires that the fabric be polyester or polypropylene with a thickness of 0.74 mm or more, a unit mass of at least 440 g/m^2, and a water permeability of 9.5×10^{3} cm/sec or greater. The fabric must have a closely woven side that is placed against the concrete and an openly woven side that is placed against the form work (Reddi 1992). To ensure that the fabric has sufficient strength to be stretched taut without tearing, the thread or yarn must have a tensile strength (tenacity) of 4.8×10^{-2} N/denier to 9.8×10^{-2} N/denier. The thread or yarn in a fabric liner would be 700 to 1,000 denier, so a single thread should be capable of suspending a mass of 5 to 10 kg without breaking.

Woven fabric liners generally require perforations in the formwork so that the water can drain through to the outside of the forms. The fabric is typically mounted on steel or wooden forms that are perforated with 3-mm-diam holes on 100-mm centers. The fabric has to be stretched and attached with glue and tape on the steel forms and with staples or other fasteners on the wooden forms. Care must be taken to prevent the fabric from stretching from its own weight after it is mounted on the formwork. Stretching removes folds in the fabric facing that destroy the smoothness of the concrete surface. If the stretched fabric becomes wet or hot prior to the placement of the concrete, the fabric may sag and fold, producing grooves in the concrete surface (Figures 4 and 5).

Problems can arise in trying to use woven fabric-lined forms more than a single time. Form-release compounds are not used on the fabric, and the lined formwork can adhere strongly to the hardened concrete. The force required to separate the forms from the hardened concrete can strip the fabric off the formwork. Particles of concrete tend to adhere to the fabric, and the force required to strip the forms increases with each use. To correct this problem, some fabrics have been squeezed under a hot roller (calendered) to deform the yarns and produce a flatter, smoother surface on the fabric. Figure 6 shows the comparative force required to strip fabric-lined forms from concrete when calendered and conventional (uncalendered) fabrics are used. Calendering reduces the tendency of the fabric to adhere to the concrete, and it appears to produce a better filter surface on the fabric.

The relative merits of different types of woven filter fabrics are difficult to assess. Peter and Chitharanjan (1995) tested nine types of filter fabrics, including polypropylene, nylon, and polyester. Concrete surfaces prepared against any of the filter fabrics showed increased strength (judged from hammer tests) and reduced water permeability when compared with concrete placed in conventional low-permeability formwork. The improvement of the surface characteristics showed no pattern that could be related to the type of fabric used or to the amount of water that had been released through the filter fabric.

Nonwoven Fabric Form Liners

Nonwoven fabrics such as thermobonded polyethylene or polypropylene have proved to be very useful as filter fabrics. The flexibility that is available in the manufacturing process offers great advantages in tailoring the pore sizes

Figure 4. Concrete surface showing marks from fabric folds that can occur from loose drainage fabric (photo used with the permission of DuPont Corporation)

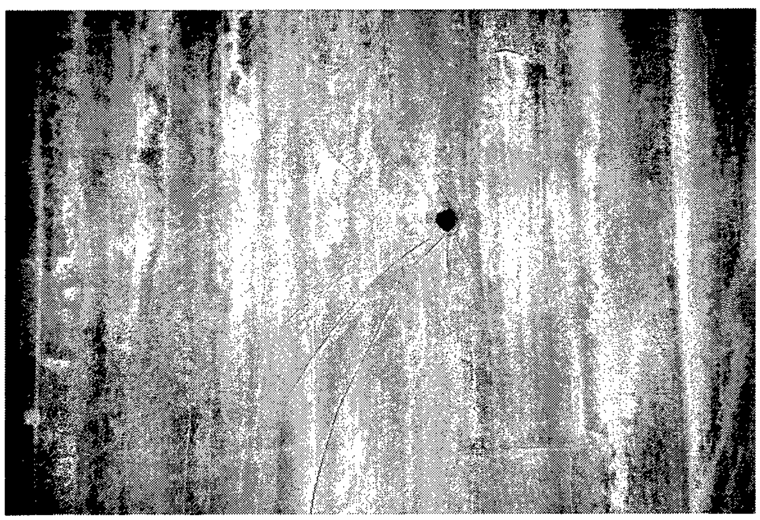

Figure 5. Concrete surface showing marks from loose fabric around a form tie hole (photo used with the permission of DuPont Corporation)

of the fabric to the requirements of having a fabric with a fine filter surface and coarser underlayer that can allow the escape of drainage water. A nonwoven fabric developed as a fabric liner may have holes in the front surface that are 0.2 to 20 microns in diameter, and holes on the reverse side between 10 and 250 μm. The fabric can be manufactured with very uniform surface pores by spraying over the base fabric with an ethylene vinyl acetate or ethylene vinyl chloride foam. The foam collapses as the solvents dissipate, and the foam layer produces a pattern of uniformly sized holes. A thin coating of oil applied over the finely porous surface allows the fabric to be removed from the concrete surface with minimum sticking (U.S. Patent Office 1992).

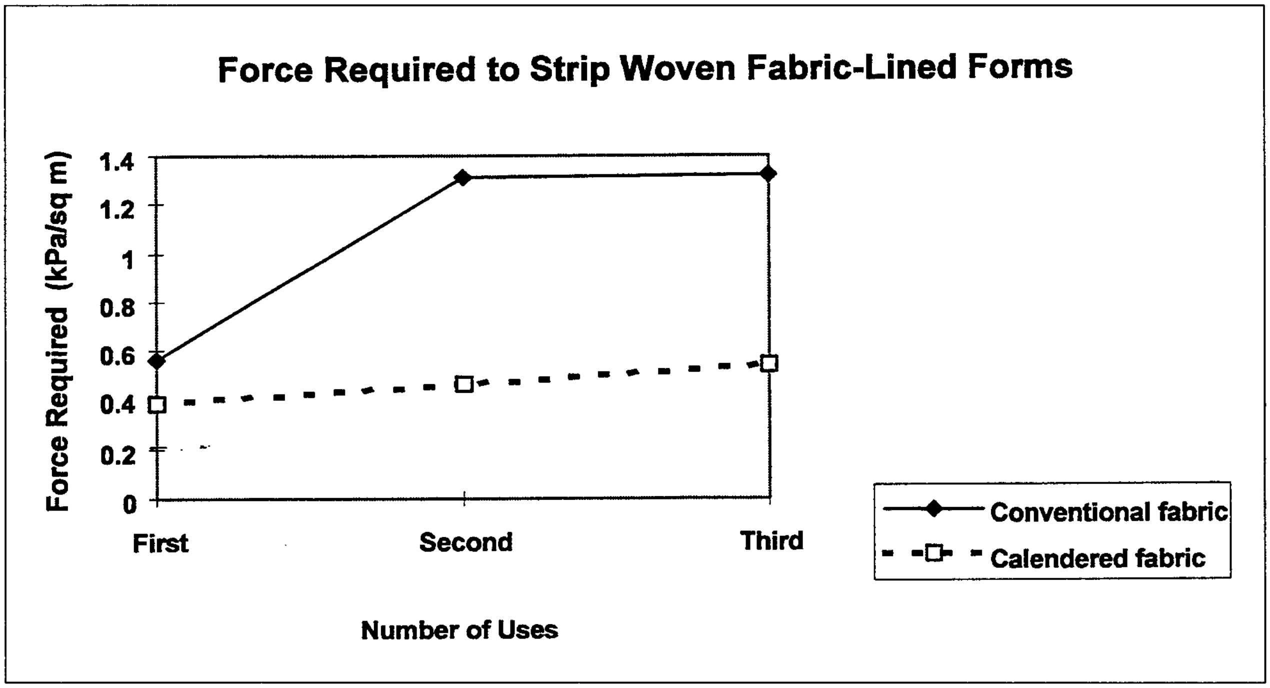

Figure 6. Force required to remove conventional and calendered fabric formwork from the surface of concrete after 48 hr of curing (data from U.S. Patent Office 1989)

Some nonwoven fabrics are backed up with a net or grid made of polyethylene. The grid is manufactured with holes 0.25 mm in diameter or larger, and the surface is formed so as to allow only part of the grid to contact the surface of the form. The goal for the grid-supported fabrics is to provide a stiff, nonwrinkling fabric layer that will allow the water from the concrete to pass into the grid and down through the bottom of the form. The grid makes it possible to drain the water from the form quickly without having to make closely spaced perforations in the form under the fabric (U.S. Patent Office 1994).

Fabrics made with bonded fibers tend to be stiffer than woven fabrics, so they resist wrinkling and sagging more effectively. The nonwoven fabrics, even those with a grid on the back (form) side, still have to be stretched and anchored to the formwork with adhesive tape or staples. Typical specifications for a nonwoven fabric would require that the materials be unaffected by the alkalinity of the concrete and be sufficiently strong so as to avoid crushing under the loading from the plastic concrete. The pore size should be such that the fabric will allow water to drain through but will retain cement particles. Fabrics with pores sizes ranging from 0.2 to 20 μm on the filter side have been found to be acceptable.

Comparative Performance of Fabric Liners

All three types of form liners (absorptive panels, woven fabrics, and nonwoven fabrics) are attempting to accomplish the same goal of reducing the w/c in the concrete at the concrete-formwork interface. Long et al. (1996) undertook a comparison of representative materials from the three types of formwork liners. All three liner types tested worked well at high w/c's (w/c = 0.65). All produced surfaces that were approximately 40 percent stronger than comparable surfaces cast against conventional (oiled plywood) formwork, as gauged by a surface pull-off test. At lower w/c's (w/c = 0.55), the absorptive panel that was tested produced a softer surface. No attempt was made to measure the absorbance of the panel or develop data on the absorption constant (C-value). Of the two fabric-based systems, the surfaces produced by the nonwoven liner were slightly stronger than those produced by the woven liner.

The absorptive panel could not be reused after the first casting since it absorbed water. When the fabrics were reused, the quality of the surfaces, in terms of both strength and permeability, was reduced. The strength of the surfaces cast against the reused liners was 8 percent lower on the third casting even though the linings were cleaned between castings. Similarly, the water absorption of the surfaces went up and the resistance to abrasion went down after the first use. These laboratory-based tests indicate that extreme care will be needed on the job site to ensure that permeable liners are not reused to the extent that the benefits of the form liners become insignificant.

3 Concrete Mixtures and Placement Techniques for Use with Permeable Formwork

Tests indicate that permeable formwork should produce improved surface characteristics (increased density and increased strength) when used with a wide variety of concrete mixtures. Concretes ranging from w/c 0.40 to 0.65 all showed improvements. The type of portland cement and the use of ground granulated blast-furnace slag or fly ash did not change the action of the permeable formwork. The use of controlled permeability formwork produced better resistance to freezing and thawing and greater resistance to deterioration due to deicing chemicals when compared with air-entrainment in blast-furnace slag cement concrete with 75 percent ground granulated blast-furnace slag replacing the portland cement (Stark and Knaack 1997, Stark and Ludwig 1997). The use of water-reducing admixtures, high-range water-reducing admixtures, or air-entraining admixtures and the placing of concretes with different slumps (50 to 210 mm) did not alter the effect of the permeable formwork (Wilson and Serafini 1996). Manufacturer's technical guidelines call for the use of concretes with slumps of 50 mm or less with permeable formwork. Concretes with high slumps tend to produce color spottiness on the finished concrete surface (DuPont Corporation 1997).

Silica fume may potentially clog some filter fabric associated with permeable formwork, so that the filter ceases to operate and the large surface area of silica fume may reduce the amount of water that is free to flow out of the concrete. Skjolsvold (1991) reported improvements in hardened concrete surfaces even when concrete mixtures having a w/c of 0.4, with an air-entraining admixture and 5 percent silica fume by mass of portland cement, were used with permeable formwork. Nolan, Basheer, and Long (1995) tested concrete with 5 percent silica fume and a w/c of 0.55 or 0.65. They concluded that the silica fume clogged the fine pores in the fabric and reduced the effectiveness of the permeable formwork. The differences in the test results may be related to the variations in the w/c and the types of silica fume that were used in the two tests. Where silica fume or other fine pozzolans (such as metakaolin) are used in concrete placed against permeable formwork, testing may be required to ensure that the pozzolan is not preventing the permeable formwork from functioning.

Interaction of Permeable Formwork and Concrete During Placement and Consolidation

Extraction of water

One objective of using permeable formwork is to ensure that the optimum amount of water is available in the concrete immediately behind the formwork. A w/c of 0.40 (or lower) is generally considered to be optimum for the production of concrete (Kosmatka and Panarese 1990, p 78). Water in excess of that called for by the w/c of 0.40 may be necessary to allow the concrete to be properly placed and consolidated unless a water-reducing admixture is used. One goal of using permeable formwork is to remove enough water from the concrete to lower the w/c from 0.45 or 0.60 to 0.40 or less.

Table 1 presents data on the quantity of water that theoretically should be removed from a 250-mm-thick wall in order to reduce the w/c from the w/c at placement (0.45 to 0.60) to a w/c of 0.40 for the entire thickness of the wall. Most of the water leaves the concrete during 90 sec of vibration, and the period of vibration is limited by the tendency of the aggregate in the concrete to separate from the paste. Tests run with concrete having a w/c of 0.50 have shown that well-designed permeable formwork can produce drainage of up to 2.0 L/m^2 during 90 sec of vibration (U.S. Patent Office 1994). Beddoe (1993) reported water losses of 1 to 2.5 L/m^2. Water loss measurements are tabulated as water drainage from the formwork. Fabric in the formwork can retain up to 0.5 L/m^2 that is removed from the concrete, but not drained. Assuming the concrete was proportioned with 340 kg of water/m^3 and that a water loss of 2.0 L/m^2 affected only the concrete in the outer 20 to 30 mm, the w/c on the surface would be 0.2 to 0.3. Farahmandpour (1992) estimated the w/c under a permeable liner was 0.35 to 0.40 compared with values between 0.40 and 0.50 for the same concrete placed in conventional wooden formwork. In all cases where careful measurements were made, the permeable formwork reduced the w/c in the surface concrete sufficiently to produce a stronger, denser surface.

Table 1
Volume of Water That Must be Removed from 250-mm-thick Concrete Panel to Produce a Water-Cement Ratio of 0.40

	Excess Water, L/m^2		
Cement Content (kg/m^3)	**w/c = 0.45**	**w/c = 0.50**	**w/c = 0.60**
300	4	8	15
400	5	10	20
500	6	13	25

After U.S. Patent Office (1994).

Densification of concrete surface

The fluid movement during consolidation of concrete carries suspended cement particles and other fines toward the interface between the formwork and the concrete. The result of this mass transfer is an increase in the proportion of cement to fine aggregate at the concrete surface. Cron (1970) reported that X-ray radiographs made from slices of concrete cut adjacent to the surfaces showed that surfaces cast against permeable formwork were visibly denser than those cast against conventional (low-impermeability) formwork. Beddoe (1993) reported a 10 percent increase in the ratio of cement to fine aggregate at the surface of concrete immediately behind permeable formwork compared with the same concrete at a depth of 5 cm. These data were collected by extracting and examining fresh concrete after placing and consolidating the concrete behind the test formwork.

Reeves (1993) documented a similar increase in density using thin sections prepared by cutting slices of hardened concrete perpendicular to the concrete surface. Samples cast against the permeable formwork showed fewer voids between the larger aggregate particles and closer packing of the particles of hydrated cement in the hardened paste at the surface of the permeable form. Reeves also noted that there was a reduction of the size and number of capillary voids in the surface zone. The control samples for comparison were prepared by casting the same concrete against steel forms. The area of pores in the controls was approximately twice (2.38 times) that in the samples prepared with permeable formwork. The observations made using light microscopy were confirmed by making pore measurements by mercury porosimetry. Porosimetry data indicated that the area of pores was 1.6 times greater for the samples cast with impermeable formwork than for the samples prepared with permeable formwork. The increased cement content behind the layer produces a denser, stronger surface on the permeable formwork.

Reduction in surface air bubbles

Air trapped in the concrete during placement works its way to the surface of the concrete and can become trapped between the concrete and the formwork. In most cases, the presence of holes, in the surface of the concrete, typically referred to as bug holes, is an aesthetics problem that does not affect the strength, durability, or service life of the concrete. Contracts written for the placement of concrete can include clauses that require the contractor to fill in all bug holes or sandblast to produce a smooth surface. In hydraulic structures, cavities in the concrete surfaces increase the turbulent flow at the concrete surface and can increase the rate of wear.

Reeves (1993) noted that the number of bug holes was reduced by using controlled permeable formwork, but on a microscopic scale the surfaces formed against the permeable formwork were rougher due to the imprint of the individual fibers of the fabric. The fibers leave channels on the surface that produce a patterning that is not obvious to the unaided eye. Work done of algal overgrowth of concrete surfaces indicated that the microscopic irregularities were not an important factor in determining if algal colonization would occur. The presence of constant moisture was the important factor. Moisture on the surface was related to the ability of the surface to absorb moisture and to remain moist due to capillary transport of absorbed water to the concrete surface. The surface porosity was more critical than the surface microrelief in algal colonization. The surfaces on concrete samples prepared with permeable formwork had less porosity and retained less moisture after wetting. The inability of the less porous concrete to maintain a constant moist surface made it less likely to be overgrown with algae.

Effects of Vibration and Pressure in Placement of Concrete with Permeable Formwork

Most of the action of permeable formwork in changing the w/c, producing transfer of cement to the formed surface, and removing trapped air bubbles occurs when the concrete in the formwork is consolidated by vibration. Usual practice in vibrating concrete placed in permeable formwork calls for the careful use of internal (generally poker-type) vibrators that are operated at distances that are greater than 50 to 100 mm from the surface of the formwork. Poker vibrators can displace or damage the fabric if they are pushed against the formwork. Generally, form vibrators or external vibrators are used only after the concrete has been initially consolidated by internal vibration. Vibration is most effective in producing high-quality surfaces if the overlying concrete exerts pressure on the concrete in the vibrated zone. Permeable formwork is least efficient for improving the concrete placed at the top of the formwork. Often, the upper 50 to 100 mm of concrete will show evidence of bug holes and a low-density surface unless it is allowed to go to an initial set, post-vibrated (or revibrated), and tamped and leveled.

Very thick lifts of fresh concrete can produce a flattening effect on permeable liners. Liners made with a drainage layer (or scrim or grid) can produce patterns on the concrete surface that reflect the shape of the drainage holes. Generally the lift should be of a thickness that will not result in pressures on the formwork that exceed 2 MPa (DuPont Corporation 1997).

4 Benefits of Using Permeable Formwork

The improved properties of concrete placed using permeable formwork can be attributed to the denser, stronger surface that the permeable formwork can produce compared with conventional formwork. Major benefits appear to result from having a smoother, denser concrete surface with fewer initial surface defects and better weathering characteristics. Permeable formwork should produce a longer service life for a concrete structure and reduced overall expenditures for repair or replacement.

Reduction in Bug Holes and Surface Defects

Bug holes in concrete surface are generally thought of as producing aesthetic problems rather than problems related to durability. Surface irregularities such as bug holes can affect performance in structures where running water and suspended materials abrade the surface of concrete because they may induce cavitation and the formation of eddies that concentrate the wear on specific points on the surface. If it is necessary to reduce the number of bug holes, there are few useful options beyond using permeable formwork. Bug holes can be reduced by placing concrete in more fluid condition (high-slump concrete); however, typically, the surface of the high-slump concrete will be less dense than with low-slump concrete and there will be a greater chance of scaling from freezing and thawing action (Reading 1972).

The ability of the permeable formwork to reduce the number of bug holes is obvious from inspection and has been clearly documented. Marosszeky et al. (1993) measured the relative areas of bug holes and smooth surfaces on blocks of concrete cast with and without permeable formwork. Blocks cast with conventional formwork have 0.59 to 1.5 percent of the surface area involved in bug holes. Surfaces on blocks cast against permeable formwork have less than 0.1 percent of the area in bug holes. Richardson (1994) reported that permeable liners were found useful in reducing the number of bug holes in concrete placed against inclined surfaces and also reduced the number of voids that typically form just below the concrete surface in inclined forms.

The architectural merits of concrete cast with permeable formwork have generally not been emphasized in recent studies because permeable formwork may produce a mottled gray and dark gray surface. The surface will be virtually bug hole-free, but may not have a uniform color (Farahmandpour 1992). Cron (1970) reports that an evaluation done on the Los Angeles Union Terminal in 1939 (3 years after the terminal was built) showed that crazing of the concrete surfaces was completely absent on the concrete cast against permeable formwork. Concrete surfaces located adjacent to the terminal and cast at the same time on conventional formwork were badly crazed. Crazing is typically associated with water loss during the early stages of curing and is accelerated by carbonation (Neville 1973). Price and Widdows (1992) showed that both early water loss and the rate of carbonation could be reduced by using permeable formwork.

Improved Resistance to Freezing and Thawing

The increase in surface density that has been observed in concrete cast against permeable formwork can potentially make the concrete[1] more resistant to damage from freezing and thawing. Table 2 summarizes the results of tests performed by a number of investigators to determine the susceptibility of concrete prepared with permeable formwork to damage from freezing and thawing. The test materials and the test methods varied, but the results uniformly indicate that permeable formwork will decrease the damage from freezing and thawing. Damage on the experimental samples was estimated at 19 percent to less than 1 percent of the damage measured on control samples cast with conventional formwork. The results are affected by the type of concrete that was tested and severity of the test conditions. However, the conclusion is that, overall, the extent of the damage to concrete cast in permeable formwork should be less than one fifth the damage to concrete cast with conventional formwork.

Reduced Rate of Surface Carbonation

The increase in surface density that has been observed in concrete cast against permeable formwork can potentially make the concrete more resistant to carbonation. Three effects occur that can potentially reduce carbonation. The smoother surface that permeable formwork imparts to the concrete reduces the area in contact with the atmosphere; the increase in density can reduce the rate of diffusion of carbon dioxide into the concrete; and the increased amount of cement in the surface layer can make additional calcium hydroxide available to maintain alkalinity at the surface. Table 3 summarizes the results of tests performed by a number of investigators on rates of carbonation in concrete prepared with permeable formwork. The test materials and the test methods varied, but the results uniformly indicate that permeable formwork will decrease the rate of carbonation. The depth of carbonation on the experimental

[1] The concrete for which data are available is, presumably, non-air-entrained. Since no such non-air-entrained concrete will be used in the future in environments where freezing-and-thawing damage is a hazard, these relationships are moot (Mather 1990).

Table 2
Summary of Data from Freezing and Thawing Tests on Concrete Placed With and Without Permeable Formwork

Reference	Cement Content (kg/m^3)	w/c	Mineral Admixture	Test Type	Loss on Scaling: Permeable Formwork	Loss on Scaling: Control Sample	Loss on Scaling: Percent Loss in Control
			Reported as kg/m^3 after 28 cycles				
Skjolsvold (1991)	384	0.42	4.7% Silica fume	Swedish SS 137244	0.02	2.54	0.01
			Reported mass change after 306 cycles				
Farahmandpour (1992)	--	--	--	--	+0.96%	-0.63%	--
			Reported loss in kg/m^2 after 28 cycles				
Beddoe (1993)	355	0.55	--	--	0.10	6.2	2
			Reported loss in kg/m^2 after 50 cycles				
			--	--	0.17	7.87	2
			Reported as g/m^2 after 5 repetitions				
Karl and Solacolu (1993)	300	0.49	Fly ash 13% of OPC by mass	Austrian Standard 3303	385 125	1995 1025	19 12
			Reported depth of standard weathering after 50 cycles (mm)				
	285	0.65	--	Austrian Standard 3303	0.1	3.3	3%
			Reported loss in kg/m^2 after 28 cycles				
Wilson (1994)	325	0.57	--	--	0.06	1.12	5
	375	0.44	--	--	0.01	0.79	1

samples ranged from 64 percent to approximately 5 percent of the depth of carbonation measured on control samples cast with conventional formwork. The results can be changed by the type of concrete tested and the severity of test conditions; however, the conclusion is that, overall, the extent of carbonation in concrete cast in permeable formwork should be generally less than 50 percent of that observed in concrete cast with conventional formwork and exposed to identical conditions of weathering.

Reduced Rate of Chloride-Ion Infiltration

Resistance to chloride-ion infiltration is extremely important to the service life of steel-reinforced concrete because the chloride ion greatly accelerates the rate of corrosion of the steel reinforcement. Even the densest phase associated with the corrosion of steel (magnetite, Fe_3O_4) occupies two to three times the space of the original steel. The stress induced by the added volume in the concrete causes cracking and spalling at the concrete surface. Corrosion that may be promoted on steel due to carbonation is slow deterioration compared with the chloride-induced corrosion, which can typically be faster deterioration than atmospheric corrosion. The fastest deterioration of the steel occurs when the pH of the concrete has dropped to 9.0 or lower and the chloride-ion concentration in the concrete adjacent to the steel is 0.77 kg of chloride ion/m^3 (Perenchio 1994).

Table 3
Summary of Data from Depth of Carbonation Tests on Concrete Placed with and without Permeable Formwork

					Depth of Carbonation (mm)		
Reference	Cement Content (kg/m^3)	w/c	Mineral Admixture	Test Type	Permeable Formwork Sample	Control Sample	Percent of Depth in Control
Skjolsvold (1991)	--	--	--	3% CO_2 60% RH[1] 22 weeks	4	12	33
Farahmandpour (1992)	--	--	--	60 days in CO_2	1.3	25.4	5
Karl and Solacolu (1993)	285	0.65	--	--	3.1	4.8	64
	300	0.49	Fly ash 13% of OPC by mass	3% CO_2 for 180 days	33.0	9.5	29
Wilson (1994)	250	0.76	--	Natural carbonation after 11 months	5	9.9	50
	288	0.66			4.2	8.1	52
	400	0.48			1.9	7.0	27

[1] Relative humidity.

Table 4 summarizes the results of tests performed by a number of investigators on rates of chloride-ion infiltration in concrete prepared with permeable formwork. The test materials and the test methods varied, but the results indicate that permeable formwork will decrease the rate of chloride-ion infiltration. The depth of chloride-ion infiltration, measured as concentration of chloride or as increased electrical conductivity in the experimental samples, was estimated at 67 percent to approximately 45 percent of the chloride-ion infiltration measured on control samples cast with conventional formwork. The results are changed by the method used to measure infiltration, the type of concrete that was tested, and the severity of the test conditions. However, the conclusion is that the extent of chloride-ion infiltration in concrete cast in permeable formwork should be less than 67 percent and generally less than 60 percent of that observed in concrete cast with conventional formwork and exposed to identical chloride-rich environments.

Table 4
Chloride Infiltration Tests on Concrete Placed With and Without Permeable Formwork

Reference	Cement Content (kg/m³)	w/c	Mineral Admixture	Test Type	Permeable Formwork	Control Sample	Percent of Control
			Reported as chloride diffusion coefficient				
Widdows and Price (1990)	288	0.66	--	TEL[1] Procedure A9	3.5×10^{-9}	7.68×10^{-9}	45
			Reported effective diffusion constant 10^{-7} cm²/sec				
Skjolsvold (1991)				AASHTO T227-831[2]	5.79	9.41	62
Farahmandpour (1992)	--	--	--	ASTM 1202[3]	4,725 coulombs	9,812 coulombs	48
			Reported as % chloride referenced to cement mass (0- to 2-cm depth)				
Karl and Solacolu (1993)	285	0.65	--	90 days 5% NaCl	1.95	2.90	67
	300	0.49	Fly ash 13% of OPC by mass	90 days 5% NaCl	2.08 2.09	3.61 3.47	58 60

[1] TEL Procedure A9 = Taywood Engineering, Middlesex, England.
[2] American Association of State Highway and Transportation Officials.
[3] American Society for Testing and Materials.

Increased Surface Strength

Surface strength measurement methods, such as rebound hammers and pin penetration tests, have typically been useful in estimating the change in the overall strength of concrete as it cures. Results of surface tests are affected by a wide variety of variables in the test specimens, including surface smoothness, type of aggregate used, and type of formwork used (Malhotra 1994). Data from rebound hammers have not typically been used to compare the surface hardness in concrete specimens. Kolek (1958) showed there is a correlation of the rebound hammer reading from concrete to the hardness measured using the Brinell method.

Table 5 summarizes the results of tests performed by a number of investigators using rebound-hammer techniques to compare samples of concrete prepared with permeable formwork with samples prepared using conventional formwork. The test materials and the test methods varied, but the results indicate that permeable formwork will increase the rebound number readings, indicating that a harder surface is produced by the permeable formwork. The rebound number readings are 10 to 18 percent higher for the samples cast against permeable formwork. The results are changed by the test method used and the type of concrete that was tested; however, the conclusion is that the rebound hammer readings in concrete cast in permeable formwork should be over 10 percent higher and possibly as much as 18 percent higher than those observed in concrete cast with conventional formwork. Marosszeky et al. (1993) reported an increase of approximately 20 percent in surface strength in concrete (mixture and test conditions not specified) cast against permeable formwork as opposed to conventional formwork.

Table 5
Surface Hardness (Rebound Hammer) Tests on Concrete Placed with and without Permeable Formwork

Reference	Cement Content (kg/m^3)	w/c	Test Type	Schmidt Hammer: Permeable Formwork Samples (rebound number)	Schmidt Hammer: Control Samples (rebound number)	Schmidt Hammer: Percent of Control
Widdows and Price (1990)	250	0.76	Schmidt hammer	39	34	114
	288	0.66		36	32	112
	400	0.48		47	40	118
Farahmandpour (1992)	--	--	Schmidt hammer	35.5	32.4	110
Karl and Solacolu (1993)	285	0.65	DIN 1048 Part 2	32	29	110
				34	31	110

In measuring the properties of concrete cast in conventional formwork, a 10 percent increase in rebound number (within the range shown in Table 5) would correlate to an increase in overall strength of the concrete of approximately 6 MPa (Zoldners 1957). The denser surface layer on concrete cast on permeable formwork extends to a depth of only a few tens of millimetres. The most logical interpretation to place on the data collected with the rebound hammer is that surface strength characteristics identical to a high-strength concrete can be achieved with a concrete proportioned to give a lower overall strength, if permeable formwork is used in forming the surface. Alternatively, if rebound hammers are used to estimate strength gain in concrete cast in permeable forms, the curves for correlating rebound hammer numbers and the unconfined compressive strength will overestimate the strength of the concrete by 10 percent or more.

Reduced Form Coating Requirements

Form-release compounds, which can clog the weave in fabric formwork or cause the fiber in the fabric to swell, are generally not used. Some of the experimental work indicates that compounds which coat the fabric liner (U.S. Patent Office 1992) can be of use, but the technical descriptions of the preparation of the formwork generally do not include the application of release compounds as a necessary procedure.

Reduced Efforts in Curing

Permeable formwork typically absorbs approximately 0.5 L of water per square metre of fabric. This water is available on the surface of the concrete to assist in curing the concrete immediately after setting. Research done by Brooks and his coworkers (U.S. Patent Office 1943) indicated that liners could provide water that is reabsorbed into the concrete during curing. After the formwork and fabric are removed, the curing requirements are similar to those associated with concrete cast in conventional formwork. Cron (1970) reported that concrete cast against absorptive liners was less affected by inadequate curing. The case-hardening effects of permeable formwork caused less moisture loss in air-cured specimens and reduced moisture absorption in moist-cured specimens. In the past when absorptive panels were used, the practice was to remove the formwork and shift the absorptive panels but to leave the panels in contact with the hardened concrete surface during curing.

Long, Sháat, and Basheer (1995) tested concrete specimens that had been cast against permeable fabric formwork or cast against conventional formwork and then cured either in air or with saturated fabric or with curing compounds. All formwork was removed after 24 hr, and all samples were maintained in an enclosure held at 20 °C and 55 percent relative humidity. The benefits in reduced carbonation and reduced chloride-ion ingress from using permeable formwork were judged to be better than those obtained using conventional formwork and any of the curing methods. Similar results were reported by Price and Widdows (1991, 1992) and Price (1992, 1993).

Reduced Surface Preparation for Coating

Surface coatings applied to concrete typically will not bond well to the new concrete surface due to a layer of soft dusty material on the surface. Preparation for applying a surface coating usually includes wire-brushing or sandblasting to provide a strong surface for coating. Bug holes typically are patched before coating. Concrete surfaces cast against permeable liners typically have a strong, bug hole-free surface, and the coating (usually epoxy or urethane) can be applied directly to the surface without the usual preparation (Anonymous 1994b).

5 Considerations in Specifying Permeable Formwork

Current Specifications for Surface Finishes

The most visible improvement that can be produced in surfaces cast against permeable formwork is a reduction in the occurrence of air-filled surface voids or bug holes. Documents outlining standard practices (American Concrete Institute 1990) recognize that bug holes can be reduced by using absorptive forms but indicate the air that causes bug holes can be dealt with by using smooth forms and the correct form-release agent.

Guidance developed for concrete in hydraulic applications recognizes the need for very smooth, formed surfaces that can minimize erosion of the concrete due to cavitation. The classes of concrete surface finishes are given in Table 6. An additional special class of surface finishes, Class AHV, is recommended for spillways, tunnels, and water passages where the water velocity is 12 m/sec or greater (Department of the Army 1994). Class AHV has exactly the same permitted irregularities as does Class A. The materials and workmanship for forming Class AHV are the same as the Class A finish requirements. Class AHV is only unusual in that the specifications for formwork for making a Class AHV surface allow the use of steel formwork, in addition to the formwork made from plywood or well-matched tongue-and-groove lumber, which is generally required for the Class A surface finish (Department of the Army 1991). Permeable or absorptive formliners are recognized as an optional method for producing surfaces that are superior in durability and resistance to abrasion (Hurd 1995); however, all specifications for surface finishes are capable of being met using conventional formwork.

Table 6
Irregularities Allowed in Formed Surfaces Checked with a 1.65-m Template

Type Irregularity	Class of Surface			
	A	B	C	D
Gradual	3 mm	6 mm	13 mm	25 mm
Abrupt	3 mm	6 mm	6 mm	25 mm

After American Concrete Institute (1997).

The selection of permeable form liners for casting concrete is dictated by the perceived need for a more durable surface and a need to greatly reduce surface irregularities. Some surface irregularities can be produced by folds in the fabric. In nonwoven synthetics, as little as 0.1 to 0.2 mm of slack can produce a fold and a visible fold mark in the concrete (DuPont Canada, undated). Nonwoven synthetics can undergo a permanent expansion up to 0.15 percent if exposed to sunlight for more than 20 min. Materials such as this are normally tensioned and stretched 0.3 to 0.5 percent while they are being mounted on the formwork to prevent folds from forming. Surface defects from folds have also been noted with impermeable form liners made from elastomers, fiberglass, or plastics (Department of the Army 1994). All form liners (permeable and impermeable) are subject to movement it they are wetted or allowed to become hot before concrete placement. Folds are minimized by specifying that liners be tensioned and anchored using tape, adhesives, staples, or screws. When care is taken to avoid folds, permeable formwork is capable of producing a dense surface with a finish that would qualify as a Class A or Class AHV surface.

Specifying the Surface Characteristics Developed by Permeable Formwork

The quality of the surface will be a function of the preparation of the formwork, the selection of the concrete mixture, and the skill in placing and consolidating the concrete. If a specification is prepared on the basis of the performance of the finished concrete, the acceptance testing must be referenced to test panels that are cast from the same concrete without permeable formwork. Acceptable limits for criteria such as carbonation, resistance to freezing and thawing, and surface hardness have to be indexed to the surfaces cast on conventional formwork that are prepared as controls. For example, examination of test results that have been reported suggest that the surfaces cast against permeable formwork should have a surface that is 10 percent stronger than the surface cast against conventional formwork based on rebound hammer tests (such as ASTM C 805) (ASTM 1998). Similarly, the requirements for resistance to damage from freezing and thawing and the rate of chloride-ion penetration and surface carbonation should be indexed to control surfaces.

6 Factors Affecting the Selection of Permeable Formwork

The major factors that can influence the selection of permeable formwork over conventional formwork are cost differences (and potential cost savings), the risk of inappropriate use, and the difficulty in handling (installation and removal), in that order (Department of the Army 1952). The cost savings are strongly related to the specific use and the service environment of the concrete. Where multiple placements are to be made, reuse of the permeable formwork becomes a critical factor.

Costs and Cost Benefits of Using Permeable Formwork

The ability to reuse permeable formwork for making the same type of placements several times depends on the type of permeable formwork used and the care taken in handling the materials. Absorptive formwork panels have always been considered by the users as single-use items (Johnson 1941, Bidel and Blanks 1942, Cron 1970). A modern version of absorptive formwork liner that uses superabsorbent polymer sheeting was also developed as a single-use system (Harrison 1991).

Textile forms consisting of a single layer that combines a filter layer and a drainage layer have been successfully reused up to five times on vertical surfaces and 15 times on inclined surfaces. The formwork panels have to be cleaned with high-pressure washing equipment between uses. A woven two-layer fabric form liner made with a polyester filter fabric and a polyethylene drainage cloth can generally be reused "about three times." The ability to reuse the two-layer woven fabric liner is related to the requirement to retension the fabric. Retensioning results in fraying the edges of the fabric and typically can be done only once (Harrison 1991).

Karl and Solacolu (1993) undertook a series of trials with nonwoven permeable form liner and found that the properties of the concrete surfaces were reduced when the fabric was used for the second and third time. On the third use, the chloride penetration and the depth of carbonation was twice as great as with a single use. They attributed the decrease in effectiveness to the clogging of the fine pores of the form panel with hardened cement paste. Attempts to clean the form panel immediately after removal were unsuccessful.

The cost of using fabric-lined formwork was estimated by Japanese construction companies at 3.5 to 4.5 times the cost of conventional formwork (Reddi 1992). Analyses prepared by the staff at the University of New South Wales indicated that the cost of fabric-lined formwork is 1.78 to 1.96 times the cost of conventional formwork (Marosszeky et al. 1993). Estimates from German projects suggest that the cost will be approximately double that of conventional formwork (Karl and Solacolu 1993). According to Reeves (1993), the cost of the liner could be assumed to be equivalent to the cost of utility-grade plywood used in constructing the formwork, approximately doubling the cost of the formwork.

Some savings can be realized by using a lower grade, less expensive wood in forming, since the wood does not come in direct contact with the concrete (Reeves 1993). All wood used with permeable liners has to be examined for retarding effects due to natural sugars in the wood. The cost savings may disappear if the less expensive wood must be coated before use. Cron (1970) noted that some cost savings were realized when absorptive liners were used because the backing forms were protected from damage and could be reused at negligible cost. High-quality framing wood lasted longer when form liners were used.

Ultimately, any arguments concerning the cost savings depend on the increased durability of the concrete that can be gained from using permeable formwork. Permeable formwork offers the greatest cost benefits in areas where concrete will experience severe conditions such as on roadways treated with deicing salts (Stark and Knaack 1997, Stark and Lugwig 1997), in marine environments (Long et al. 1994), and in areas where heat and high-salt content combine to reduce the service life of structures made with steel-reinforced concrete (Price 1992). Permeable formwork becomes a very useful option in situations where repairs will be difficult and costly. For example, nonwoven permeable formwork was used to cast the ice shields used to protect the piers on Confederation Bridge across Northumberland Strait between New Brunswick and the Canadian mainland (DuPont Corporation 1998), and woven permeable formwork was used in critical containment structures in nuclear power plants and prefabricated concrete tunnel sections (Kumagai Gumi Limited 1998). In hydraulic structures, such as channel linings and spillways, no method other than permeable formwork will permit concrete to be cast with a strong, smooth sloping surface, free of bug holes (Richardson 1994).

Any analysis of the costs of using permeable formwork must also address alternative strategies for developing concrete with greater durability and an extended service life. The effects of silica fume admixture, the use of permeable formwork, and the application of a silane coating were examined by Nolan, Basheer, and Long (1995). Durability was estimated based on the air permeability, sorptivity, and surface strength of concrete test specimens. The use of permeable formwork produced the greatest reduction in air permeability and also produced a significant reduction in sorptivity. Permeable formwork has the advantage of producing permanent surface changes that coatings cannot produce. Silica fume increased the critical factors related to durability, but used alone did not improve the surface as much as the permeable formwork did. Overall permeable formwork provided the most effective procedure for improving durability. Marosszeky et al. (1993) compared the cost of using permeable formwork to produce a durable structure and the cost of increasing the strength of the concrete to produce equal durability characteristics while using conventional formwork. The authors concluded that concrete with 30-MPa unconfined compressive strength placed with permeable formwork would give a surface with the same durability as 50 MPa concrete placed with conventional formwork. They also concluded that, for the example structure being studied, an approximate 4-percent cost saving could be realized by using permeable formwork on the exposed surfaces of the concrete.

Misuse of Permeable Formwork

The techniques for using permeable formwork have developed to such an extent that the chance of misusing this technology is slight. Form liner products that have acceptable performance and contractors with experience using permeable formwork are available. The level of performance in terms of improvements in the surface of the concrete can be specified, and methods are available for evaluating the concrete surfaces produced using well-accepted test methods. Limitations on the concrete mixtures that can be used with permeable formwork have been explored, and the specifications can be used to prevent inappropriate mixtures from being used. Concerns such as specification of the frequency of reuse that will be allowed and a specification for the techniques to be used in cleaning the forms between uses (if indeed they can be reused) have to be addressed in any contract. Laboratory work (Long et al. 1996) and field tests (Karl and Solocolu 1993) indicate that benefits from the formwork liners can drop off significantly if the filter fabric cannot be restored.

Difficulties in Handling

Attaching a liner to the inside surface of formwork requires additional materials and increases the labor involved in assembling the formwork. Installing absorptive panels requires skill and effort comparable to installing siding or insulation board. Fabric liner installation requires approximately the same skill and effort that would be involved in laying carpet. Labor for installation of fabric liners has been estimated at 0.08 man-hour/m^2 (DuPont 1995); absorbent panels would probably require the same effort.

Absorbent panel liners have typically attached directly to the formwork with screws, and spaces were allowed between liner panels so that the panels could expand when they absorbed water. By gauging the opening carefully, a smooth surface would be produced with the expanded panels butting up against each other. When fabric liners are used, care must be taken in tensioning the fabric liners to prevent wrinkles and creases. Tensioning is typically done by pulling the fabric around the edge of the formwork and stapling the fabric on the side or back of the formwork, not on the front face. Fabric typically must be stretched to produce an elongation of 3 to 5 mm per metre of length. Fabric materials manufactured with stiff backing do not require stretching and can be fastened to the front of the formwork. Fabric liners are typically attached to metal formwork by bolting wooden members to the edges of the forms and stapling the fabric to the wood. Fabric with stiff backing can be attached directly to the metal forms with adhesive or tape. Seams between sections of fabric liner can be sealed with tape where producing a smooth surface is critical.

Once mounted on the form, some fabric liners may stretch, sag, or distort if they are allowed to get wet or become hot. The liners should be kept dry, and the attachment of the liners should be scheduled so that the temperature does not increase more than 10 °C prior to placement of the concrete (DuPont Canada, undated).

If fabric-lined formwork is to be reused to produce aesthetically pleasing concrete surfaces, care has to be taken to avoid having conventional uncoated steel in the staples or in metal forms because of rust. It is not possible to clean the rust from a conventional steel form without removing the fabric, and the rust will bleed through the fabric and stain the concrete surfaces. Similarly, metal fasteners such as staples will produce stains when they come in contact with fresh concrete. Nonrusting metals such as stainless steel are preferred in the formwork, and stainless steel staples and screws are the preferred fasteners.

7 Long-Term Testing of Surfaces Formed with Permeable Formwork

All of the major types of permeable formwork have been successfully used in field applications to produce smooth cast concrete surfaces free of bug holes. Hundreds of construction projects, in Japan, Europe, Canada, and the United States, have used permeable formwork in placing concrete. Considering the large number of applications, and the large volumes of concrete involved in the placements, it is surprising that field documentation of the long-term effects of permeable formwork (in terms of reduced damage to the surfaces from freezing and thawing and reduced carbonation) is generally rare.

Cron (1970) pointed out that the Bureau of Reclamation retained in its test area in Denver the original acceptance panels cast against plywood and against two of the absorptive panels in common use in the 1940's, as well as samples cast against the fabric-covered absorbent panels used in 1944. None of the test panels and none of the full-scale field placements involving millions of square feet of surface had been investigated. Because no comprehensive service evaluation had ever been made during the 26 years since the concrete was placed, the superiority of the test panels in resistance to weather, compared with concrete formed against conventional wooden formwork, was unknown. In 1970, there was no interest in a test program because virtually no one in the United States was using absorptive formwork and only one brand of liner was still on the market.

Basheer et al. (1995) reported on an investigation undertaken on three bridge piers built in Northern Ireland where one half of each pier had been cast against permeable formwork and one half had been cast against conventional formwork. Six months after placement, the concrete cast using the permeable formwork had a surface tensile strength (measured in a pull-off test) that was approximately 27 percent greater than the same concrete cast against conventional plywood formwork. The concrete cast against the permeable formwork showed much lower air permeability measured using the Queen's University air permeability testing apparatus (Basheer 1993). The water sorptivity test conducted using the method outlined in Basheer (1993) was significantly lower on the concrete surface cast against the permeable formwork. The average electrical conductivity of the concrete cast against the permeable formwork was only marginally higher than that cast against the conventional formwork. According to measurements made 3 years after placement, all of the piers had electrical resistivities that would be classed as indicative of a probable high rate of corrosion based on the scale established by Longford and Broomfield (1987).

Wilson and Serafini (1996) reported a significant long-term reduction in chloride-ion content in concrete placed in the splash zone at Port Rashid, United Arab Emirates, when the concrete had been cast against permeable formwork as opposed to concrete cast against conventional formwork. Samples were taken after a 3-year exposure to saltwater and heat. Analyses showed a 35 percent lower chloride ion concentration at a depth of 5 mm in the concrete that had been cast against permeable formkwork. Samples taken at a depth of 17.5 mm showed a 65 percent reduction in chloride-ion content.

The small number of field measurements that have been made on concrete cast with permeable formwork appear to confirm the effects observed in laboratory tests. Additional field studies that go beyond the studies of samples that are 3 years old are needed to demonstrate the effectiveness of permeable formwork in increasing the service life of concrete.

8 Example Applications of Permeable Formwork

Permeable formwork has been used on hundreds of concrete structures around the world. The improved surface characteristics are especially important in marine structures and in areas where deicing salts are used. The improved surfaces also have benefits in potable water tanks or waste treatment plants where the concrete can be coated with a minimum of preparation.

Ice Shields for the Confederation Bridge, Canada

Nonwoven fabric form liners were used in constructing the conical concrete skirts placed around the supporting piers for the Confederation Bridge, spanning 8 miles (13 km) across Northumberland Strait between New Brunswick and Prince Edward Island. A concrete collar or skirt encircles each of the round piers to protect them from ice floes that pass through the channel. The original plans called for a steel collar or cone, but monolithic reinforced concrete was considered more cost effective. The protective cone is 20 m in diameter and 13.6 m tall. The cone extends 10 m above water level and 6.4 m below. The outer surface slopes inward at a 52-deg angle. The drifting ice floes ride up the sloped concrete surface and break under their own weight (DuPont Corporation 1998). Figure 7 shows the fabric-lined wooden formwork being put in place over the base of the pier. Figure 8 shows the cast concrete shield after the formwork is stripped. A close-up view of the surface where the fabric liner ended shows the contrast of the bug-hole free surface under the permeable fabric-lined formwork and the surface under the conventional unlined wooden formwork.

Immersed-Tube Precast Tunnel Segments

Woven fabric liners have been used in casting reinforced concrete tunnel sections that can be floated into position and sunk to form tunnels. The Japanese textile form method was employed to produce a denser surface of the

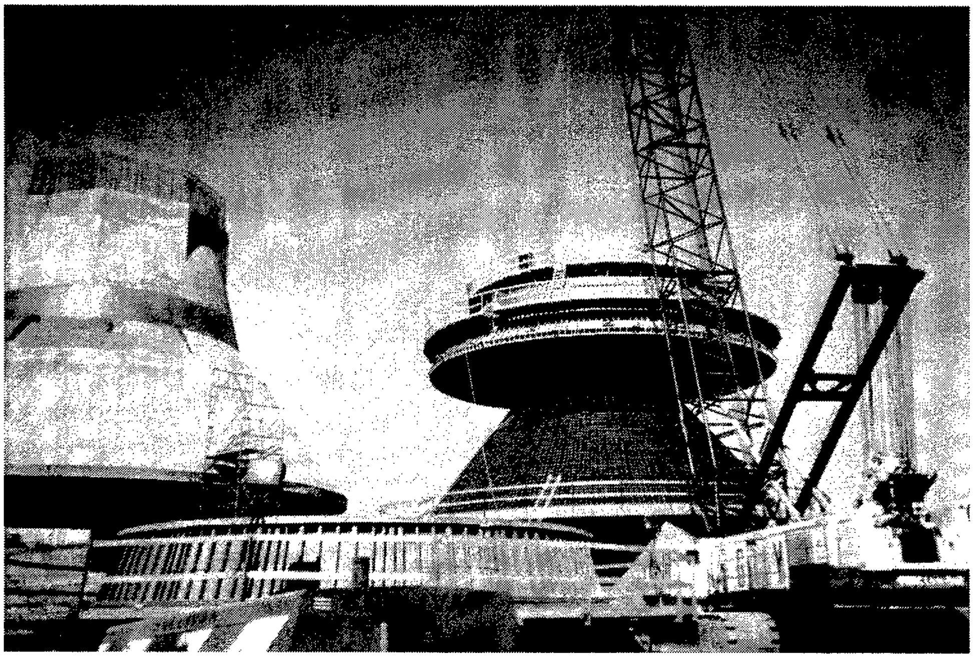

Figure 7. Fabric-lined wooden formwork being placed around the base of a pier for the Confederation Bridge, Canada (photo used with the permission of DuPont Corporation)

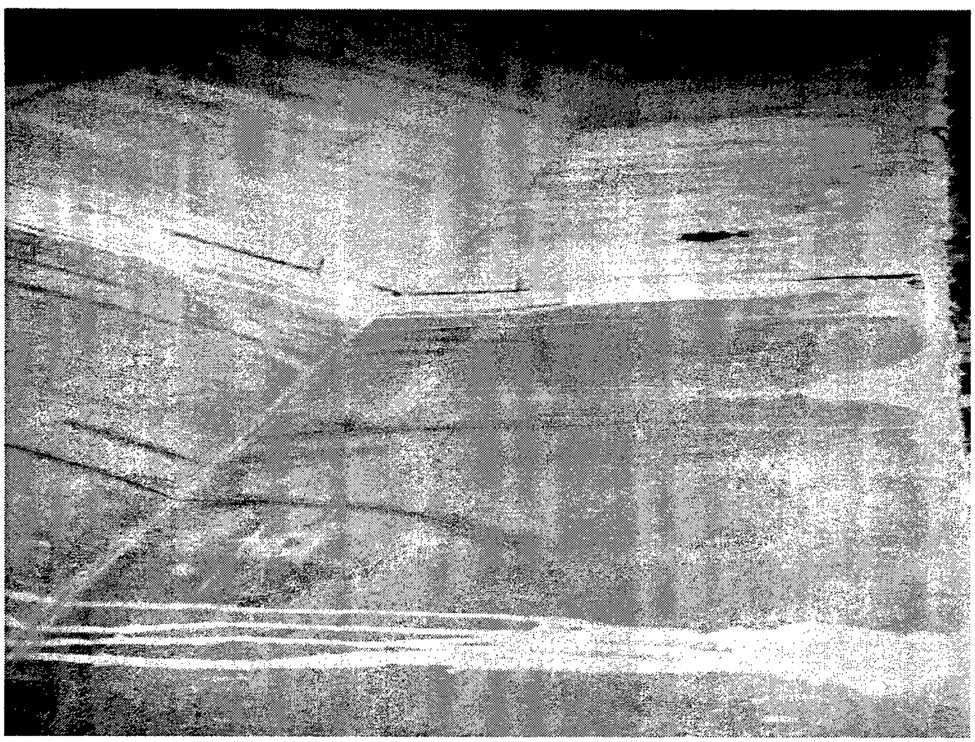

Figure 8. Smooth concrete surface produced by the fabric liner on ice shields for Confederation Bridge, Canada (photo used with the permission of DuPont Corporation)

concrete and reduce the risk of corrosion from seawater (Kumagai Gumi Limited 1998). The Western Harbour Crossing in Hong Kong and the Sydney Harbour Tunnel in Australia were constructed using this technique.

Concrete Barriers for the Champlain Bridge, Canada

For the Champlain Bridge (in Montreal), non-woven fabric form liners were used in preparing the precast concrete New Jersey-style traffic barriers. The new barriers replaced existing barriers that had deteriorated, largely due to the road-deicing salt (estimated salt use was over 3,000 metric tons per year). An estimated 57 percent of all of the exposed concrete surface on the bridge had spalled. The new 6-m-long barrier segments were cast using fabric-lined steel molds (Figure 9). A total of 2,600 m of barriers was cast using 1,550 m^3 of concrete. The steel forms were lined with fabric by stapling the fabric to bolted-on wooden attachment plates. Liners were used for only one casting. The engineering team used a high-strength concrete mixture (specified to have 35 MPa unconfined compressive strength), epoxy-coated steel reinforcement, and permeable fabric-lined formwork with the goal of creating a smooth-surfaced concrete barrier structure with a minimum 25-year life expectancy (Figure 10).

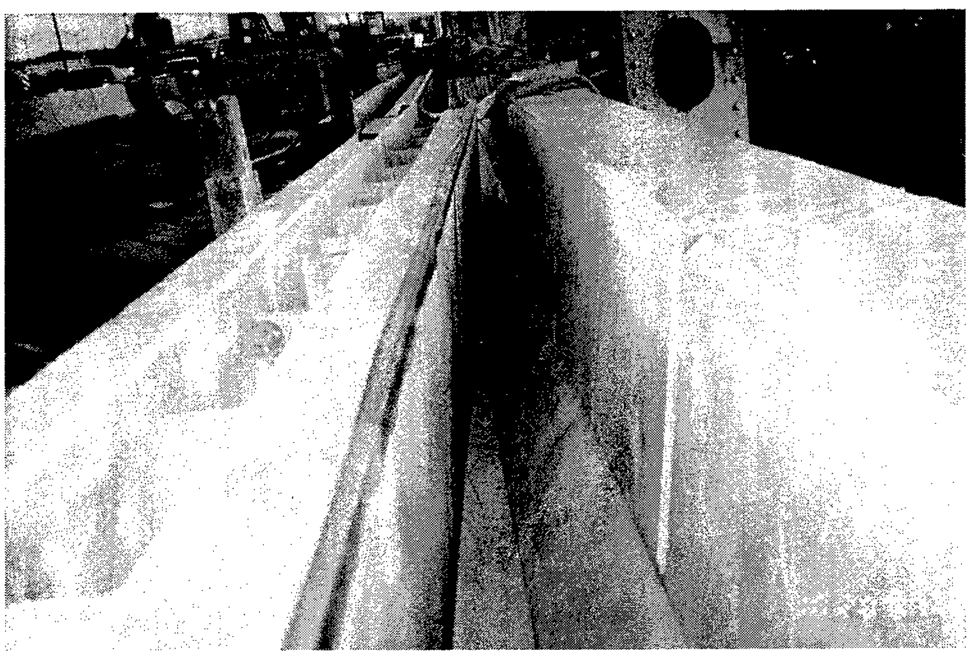

Figure 9. Formwork for New Jersey-style barrier with fabric in place (photo used with the permission of DuPont Corporation)

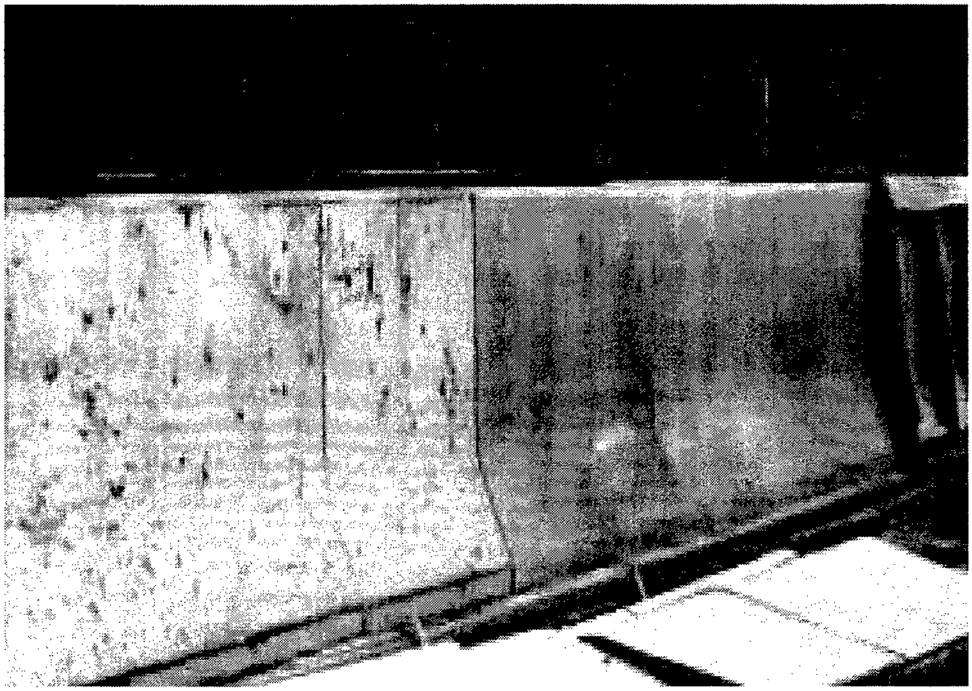

Figure 10. New Jersey-style barriers cast without (left) and with (right) fabric liners. Note lack of bug holes when fabric liners were used (Photo used with the permission of DuPont Corporation)

9 Conclusions and Recommendations

Conclusions

A review of permeable formwork and its use in placing concrete indicates the following:

a. Properly designed permeable formwork will reduce the w/c in the concrete immediately behind the formwork after the concrete is placed and vibrated. The change can affect concrete to a depth of 25 to 50 mm.

b. The w/c decreases because water can drain away from the concrete immediately behind the permeable formwork and because fine materials including cement collect in the volume of concrete immediately behind the filter layer in the formwork.

c. The ability of the permeable formwork to allow air to pass out from behind the formwork results in the production of a nearly bug hole-free surface that appears to be less subject to crazing.

d. The decreased w/c in the surface concrete results in the production of a stronger, denser surface that has increased resistance to freezing and thawing, a reduced rate of surface carbonation, a reduced rate of chloride-ion infiltration, and increased surface strength.

e. The denser surface produced in concrete cast behind the permeable formwork makes the concrete less sensitive to poor curing practices.

f. The cost of using permeable formwork can vary greatly among job sites. However, the cost of using permeable formwork will generally be double that for conventional low-permeability formwork.

g. Cost savings can be realized in the extended life of any wooden formwork used behind the filter fabric, the ability to proceed without applying any form-release compounds, the decreased cost of final surface preparation (if coatings are to be applied to the finished concrete), and the increased service life of the finished concrete.

h. Using permeable formwork does require that additional care be taken in planning the concrete placement so that the filter fabric is not exposed to conditions that might cause the material to sag or stretch.

i. Care must be taken to follow the manufacturer's recommendations in vibrating the concrete behind the formwork because of problems related to damaging the formwork and in making the formwork function properly near the tops on the forms where the pressure of the filter fabric is at its lowest.

j. Permeable formwork will function with almost any concrete mixture, although a high proportion of fines, such as silica fume in the mixture, may cause the filter to become clogged, and reduce the effectiveness of permeable formwork.

k. Specifications can be written so that the surface improvements that permeable formwork is capable of producing can be obtained by a contractor.

Recommendations

Based on this review of permeable formwork technology, the following recommendations are made:

a. Condition surveys should be undertaken on older concrete structures that contain surfaces cast against permeable and conventional (impermeable) formwork with the goal of evaluating the long-term benefits of using permeable formwork.

b. Guidance should be developed that will allow permeable formwork to an option for the placement of concrete in areas where freezing-and-thawing and salt damage make concrete placed with conventional formwork susceptible to damage. Guide specifications should be developed that address material properties (e.g., pore size, crushability, water retention) and/or performance of finished concrete (i.e., increased surface hardness, resistance from damage by freezing and thawing).

c. Guidance should be developed on the use of coatings over the denser surfaces produced by permeable formwork, with the goal of reducing the cost and effort in coating these specially prepared concrete surfaces.

d. Investigations should be undertaken on the potential use of permeable formwork in the repair of vertical and inclined surfaces. Such investigation should include a comparison of effectiveness, cost, and other factors for different materials and systems on the market.

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13.ABSTRACT *(Maximum 200 words)*

Permeable framework is a special class of lined formwork used to produce improvements in the strength and durability of concrete. The bracing and the liner in the formwork are engineered to resist the pressure of plastic (or fresh) concrete, but to allow trapped air and excess water to pass through and be removed during concrete placement and consolidation. The objective in using permeable formwork is to eliminate voids on the surface of the concrete (bug holes) and to increase the strength and durability of the concrete surface immediately behind the formwork.

A review of permeable formwork and its use in placing concrete was conducted. Methods, techniques, and materials are discussed, and example applications are described.

Benefits of using permeable formwork include a reduction in bug holes and surface defects, improved resistance to freezing and thawing, reduced rates of surface carbonation and chloride-ion infiltration, increased surface strength, reduced form coating requirements, reduced efforts in curing, and reduced surface preparation for coating.

The cost of using permeable formwork varies greatly among job sites. However, the cost of using permeable formwork will generally be double that for conventional impermeable formwork. Cost savings can be realized in the extended life of any wooden formwork used behind the filter fabric, the ability to proceed without applying form-release compounds, the decreased cost of final surface preparation (if coatings are to be applied to the finished concrete), and the increased service life of the finished concrete.

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