The role of Controlled Permeability Formwork in life cycle design

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**ABSTRACT:** In recent years the number of reinforced concrete structures experiencing premature deterioration has grown considerably. It is worth noting that in many cases the structures in question were constructed less than 20 years ago. However, most were designed with an anticipated design life of approximately 100 years. This has forced governments to make provisions in routine maintenance budgets for structural rehabilitation, a process that is both expensive and also disruptive to the travelling public.

This paper shall compare concrete cast against conventional Impermeable Formwork (IMF) and demonstrate how a Controlled Permeability Formwork (CPF) liner can reduce initial construction costs, whilst at the same time achieving durability, through the natural enhancement of the near surface cover.

1 INTRODUCTION

The premature deterioration of reinforced concrete structures now accounts for a significant proportion of annual maintenance budgets worldwide. To place this in context, within the UK it has been estimated that approximately £100 m per annum is spent on structural rehabilitation. This figure however is dwarfed when compared to the annual cost in the United States where the repair, protection and strengthening of deteriorating structures is estimated between $18 (£9) and $21 (£10.5) billion, Emmons and Sordyl (2006).

Case studies from around the world clearly demonstrate that modern structures despite significant advances in the field of concrete technology continue to deteriorate prematurely from either chloride-induced corrosion, carbonation-induced corrosion, freeze thaw action or sulfate attack Silva-Araya et al. (1997), Wallbank (1989) & Radic et al. (2006).

With the advent of EN206 the specification of concrete rightly moved the emphasis of concrete grade and refocused upon achieving concrete durability. This was achieved by mandating specifier’s of structural concrete to consider the environment within which a designed element would function. In so doing the hope was, structures constructed in aggressive environments would be robust and therefore capable of withstanding the harsh environmental conditions they would operate within. However despite limits on minimum cement content, levels of cement replacement, guidance on cover, exposure classes, cement types etc. the code fails to satisfactorily address the problem of concrete cast against Impermeable Formwork.

Even with replacement cements, the inclusion of admixtures or the application of surface treatments or coatings, premature deterioration of modern concrete structures continues to be a reality, is this really a tenable position for Clients, Engineers and Concrete Technologists?

1.1 The concrete surface

To facilitate the placing and compaction of in-situ concrete, it is necessary to increase the volume of free water above that required to attain full cement hydration.

Hydration is caused by the reaction of cement particles and water. During this process, heat is evolved and a network of crystals form and grow (Figure 1), the rate at which this occurs depends primarily upon the cement type and the ambient temperature.

The hydration reaction can only take place if there is sufficient moisture is present within the concrete matrix. This is why we cure concrete to maintain the moisture level. With some blended cements hydration may continue for several years but the majority of it occurs in the first twenty-eight days. The crystal network created becomes very dense and this is what makes internal bulk concrete virtually impermeable (Figure 2) and in turn durable.

Structural designers and concrete specifier’s are under the false illusion that a given cement content and
Figure 1. This illustration shows the first steps of hydration – crystals have started to form around the particles of cement.

Figure 2. This illustration shows the crystal growth reaching and adhering to the aggregate particle.

water cement ratio, homogeneously mixed and placed within a structural element, will have the same levels of cement and w/c ratio throughout the cast element. The reality however is somewhat different.

Once fresh concrete is placed within a steel, timber or plastic formwork, the compaction process and resultant hydraulic pressures force excess mix water and entrapped air towards the IMF surface. As the formed surface is impermeable the water and air are retained, Price and Widdows (1991). Visually the most obvious sign of this is the presence of blowholes and surface blemishes following removal of the formwork. Although it is industry practice to “make good” surface defects, this in itself will not enhance the quality of the surface as this has now been determined.

The net result is the creation of a near surface cover with a lower cement content and higher water/cement ratio than specified. Or to put it another way, the cover irrespective of cement type, grade or admixture etc. will be of poorer quality compared to the bulk concrete beyond the reinforcement layer, McKenna (2007).

For reinforced concrete elements a key component in attaining their structural design lives is to first ensure the initial line of defence “the cover”, is fit for purpose. Were this to be assured, it would not be unreasonable to assume a high level of durability could be attained, for:-

“What is vital is to strive to achieve the best in cover concrete: “best” means excellent compaction without trapped air bubbles or bleed water; it also means not allowing escaping water locally to increase water-cement ratio, the prevention of leakage of neat cement paste, and the avoidance of pocket marks and surface blemishes in general. Achieving all this requires a concentrated effort during placing and compaction as well as good quality formwork without blobs of form-release oil on its surface. In this respect, controlled permeability formwork seems to be beneficial, not only because it gives a better finish but also because it leads to less patching, which may be vulnerable to external attack.”

Neville (2006)

2 CONTROLLED PERMEABILITY FORMWORK

2.1 The principle

CPF is a thermally bonded polypropylene fibre membrane that is tensioned and attached to the internal face of vertical, soffit or inclined formwork with staples or other fixing devices. Once in place the concreting may be undertaken conventionally.

Unlike IMF cast surfaces, a CPF liner provides a mechanism through which surplus water and air can pass in a controlled manner through a permeable fibre membrane. Although the liner facilitates excess water removal, the filter is fine enough to retain cement particles carried within the water at the filtering side, McKenna (2002).

This results in the creation a uniform surface relatively free from blowholes and other surface blemishes when compared to IMF concrete (Figure 3). The net effect is a quantifiable reduction in the near surface w/c ratio and porosity, thereby improving the surface strength, durability and over all appearance of the finished concrete.

2.2 The mechanism

The three basic elements of a manufactured CPF system, as illustrated within Figure 4 these comprise:

A filter membrane:

to allow the passage from the concrete of excess water and air, but designed with a pore size to retain the majority of cement and other small fines.
A drain:

through which entrapped water and air may escape.

A structural support:

commonly timber, steel or plastic a structural formwork support provides a face against which the CPF system may be attached.

The liner thickness is typically 2.5 mm with the filter portion having a pore size of circa 0.050 mm. They are chemically inert and robust with high tear strength and puncture resistance, therefore suitable for many of the harsh conditions that may be encountered on a typical site.

It should be stated that due to the polypropylene filter and drain elements been thermally bonded, the use of release agents are not required as the liner easily debond from the concrete whilst remaining attached to the formwork during striking of the shuttering. This has been found to be beneficial for potable water retaining structures as concrete cast against CPF is resistant to bacterial growth in wet/dry environments, Wilson (2006).

2.3 Liner re-use

Liner re-use is feasible and the research suggests three to four uses are possible where durability is the primary consideration, however where aesthetic removal of surface blemishes is the main concern, up to six uses have been achieved, Wilson (2006). High power pressure water jets have been found to achieve the best results when cleaning the liner pores between uses. This is typically undertaken whilst the liner remains tensioned to the freshly struck formwork.

2.4 Performance of CPF over IMF

A considerable body of published material (laboratory and in-situ research papers/reports) now exists on the benefits afforded to the cover area by CPF. Irrespective of grade, cement type or admixture used, the literature suggests CPF performance is superior to concrete located beyond the reinforcement layer or cast against IMF. The following tables summarise the comparative performance of CPF in the cover area across a number of properties from surface strength to durability.

Table 1. Comparative improvements in laboratory cast concrete with a CPF liner.

<table>
<thead>
<tr>
<th>Test(1)</th>
<th>Design strength(2)</th>
<th>Cement type(3)</th>
<th>Admixture(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebound</td>
<td>+45%</td>
<td>+24%</td>
<td>+45%</td>
</tr>
<tr>
<td>Pull Off</td>
<td>+100%</td>
<td>+100%</td>
<td>+75%</td>
</tr>
<tr>
<td>Cement Content</td>
<td>+36%</td>
<td>+40%</td>
<td>+38%</td>
</tr>
<tr>
<td>W/C Ratio</td>
<td>−0.16</td>
<td>−0.20</td>
<td>−0.30</td>
</tr>
<tr>
<td>ISA(10)min</td>
<td>−60%</td>
<td>−60%</td>
<td>−60%</td>
</tr>
<tr>
<td>Capillary porosity</td>
<td>−20%</td>
<td>−30%</td>
<td>−35%</td>
</tr>
<tr>
<td>Abrasion</td>
<td>−75%</td>
<td>−70%</td>
<td>–</td>
</tr>
<tr>
<td>Freeze Thaw</td>
<td>−50%</td>
<td>−65%</td>
<td>–</td>
</tr>
<tr>
<td>Carbonation</td>
<td>−100%</td>
<td>−50/100%</td>
<td>–</td>
</tr>
<tr>
<td>Chloride</td>
<td>−65%</td>
<td>−50%</td>
<td>–</td>
</tr>
</tbody>
</table>

Notes:
1. Comparative performance between IMF and CPF concrete
2. Average of 3 design strengths (C20/25, C30/37 and C35/45 N/mm²)
3. Average of 5 cements types (PC, PFA, GGBS, MK & CSF)
4. Average of 4 admixtures types (WR, SP, AE and WP)
Table 2. Comparative improvements in site concrete cast with a CPF liner.

<table>
<thead>
<tr>
<th>Test (1)</th>
<th>New sites (2)</th>
<th>Old sites (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebound</td>
<td>+40%</td>
<td>+38%</td>
</tr>
<tr>
<td>Pull Off</td>
<td>+60%</td>
<td>+100%</td>
</tr>
<tr>
<td>Cement Content</td>
<td>+36%</td>
<td>–</td>
</tr>
<tr>
<td>W/C Ratio</td>
<td>–0.26</td>
<td>–</td>
</tr>
<tr>
<td>ISA(10)min</td>
<td>−50%</td>
<td>−65%</td>
</tr>
<tr>
<td>Capillary porosity</td>
<td>−30%</td>
<td>−40%</td>
</tr>
<tr>
<td>Abrasion</td>
<td>−60%</td>
<td>–</td>
</tr>
<tr>
<td>Freeze Thaw</td>
<td>−60%</td>
<td>–</td>
</tr>
<tr>
<td>Carbonation</td>
<td>−100%</td>
<td>–</td>
</tr>
<tr>
<td>Chloride</td>
<td>−75%</td>
<td>−75%</td>
</tr>
</tbody>
</table>

Notes:
1. Comparative performance between IMF and CPF concrete
2. Average results across 10 UK construction sites
3. Average results across 2 existing construction sites (6+ years old)

The results presented are based on research carried out both on site and in the laboratory for a range of structural elements cast against CPF and IMF, McKenna (2002). For the properties examined, the benefits of CPF were noted to be in line with the literature. Once again irrespective of grade, cement type or admixture, CPF concrete was found to be superior in terms of:

- Improved resistance to aggressive chemicals
- Improved resistance to chloride diffusion
- Improved resistance to carbonation
- Improved freeze thaw resistance
- Improved abrasion resistance
- Improved surface hardness
- Improved tensile strength
- Improved Durability
- IMF cast concrete

2.5 Cost benefits

Under the majority of circumstances incorporating a CPF liner into a project will increase initial construction costs. However savings can be achieved by taking the following into consideration:

- Liner reuse up to 3–6 times depending on requirement
- Material savings on release agents
- Material savings on curing agents
- Significantly less cosmetic repairs required
- Reduced cleaning and maintenance of formwork
- Possibility of using lower grade formwork
- Possibility of using less cement
- Non-hazardous to health, unlike silanes which have cancerous properties, therefore COSHH exempt
- Environmentally friendly as liners may be recycled following use.

Although Contractors can reduce the initial material cost of the CPF liner, by far the biggest economic saving will be the reduction in maintenance and repair budgets of structures in service.

2.6 Early thermal cracking

To cater for the thermal effects that arise from the hydration of concrete, a greater quantity of reinforcement is incorporated into a structural element. Were this not the case then thermal cracking of the structural element would occur within 24 hours of the concrete placement. One of the benefits of employing a CPF is its ability to increase the cement content within the near surface. McKenna (2002 and 2007) suggests this is in the order of 50–100 kg/m³ over the specified cement content. A review of the available literature has shown CPF has been used in-situ on projects with large surface areas, in all cases Early Thermal Cracking did not occur.

A primary reason for this is down to the systems ability to hold water within the filter and drain elements. Under capillary action some of this water can imbibe back into the concrete to assist curing. Thus in the crucial period before the formwork has been struck the element has already undergone a degree of curing. Therefore normal curing practices can only serve to further enhance the life span of the structure.

3 CONCLUSIONS

Conventionally cast concrete irrespective of grade or cement type, consistently fails to deliver cement contents and water/cement ratios as specified for cover concrete. The result is an opening up of the pore structure for aggressive environments to initiate corrosion. Although this defect is presently addressed via the application of surface treatments, coatings, the introduction of corrosion inhibitors or the installation of cathodic protection etc. this paper has demonstrated a viable alternative exists.

The fundamental difference between a Controlled Permeability Formwork and other durability enhancing systems is, during the casting process, a CPF liner will uniquely modify the properties of freshly placed concrete, thereby improving surface strength, durability and overall appearance of the finished concrete.

CPF Liners are a proven method of enhancing the cover area of structural concrete. In aggressive environments, today’s designers no longer need to accept inferior or deficient concrete surfaces, nor need apply finite life protection systems. Moreover, Clients can finally be offered the grail of research into concrete durability – concrete structures with a level of durability far superior and more cost effective compared to similar concretes cast against IMF.
REFERENCES


