Patch repair: compatibility issues

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ABSTRACT: Repair of any concrete structure results in formation of complex, at least two-component repair systems. Compatibility approach is treated as a basic requirement during selection of repair material. Recently, the understanding for compatibility requirements in repair systems approach is demonstrated in many papers. The aim of this paper is analyzing the compatibility between repair materials and concrete substrate in the case of patch repair. The compatibility issues were discussed in light of the various requirements which determine the mathematical space of loads, including chemical, mechanical and other physical (mainly thermal) loads. N-dimensional compatibility space is created, taking into account selected patch material control parameters. The requirements for good compatibility between repair material and concrete substrate can be formulated by using mathematical inequalities, where the variables are the material control parameters. The effects of properties of the both repair material and concrete substrate were analyzed using computer system ANCOMP developed at Warsaw University of Technology. Usability of this approach was demonstrated using selected case study as an example.

1 INTRODUCTION

Compatibility is considered as a basic rule for selection of materials for repair of concrete structure (Vaysburd 2006). The compatibility concept has been formulated in the early nineties (Czarnecki et al. 1992; Emmons & Vaysburd 1992). It covers four types of compatibilities (Emmons et al. 1993, Morgan 1996):

- dimensional (E modulus, creep, shrinkage, thermal dilatation, geometry of sections),
- permeability,
- chemical,
- electrochemical.

Recently, the understanding for compatibility requirements in repair system is demonstrated in many papers (eg. Czarnecki et al. 2000, Courard & Bissonnette 2007, Schueremans et al. 2011). So far the compatibility was in practice dealt with intuitively. This approach can be found in the new European Standard EN 1504, where the general requirement for repair was formulated as: "the achievement of the compatibility of the original concrete and reinforcement with the protection or repair products and systems and compatibility between any different products and systems, including avoiding the risk of creating conditions which may cause corrosion".

Similar requirement it can be found in ACI Concrete Repair Manual (2003): "It is also important that the repair material has mechanical properties compatible with those of the substrate concrete to ensure that the materials will act as one and no material failure will occur". Additionally some rules for selection of repair materials are formulated: "If some properties of the repair material are greatly different from those of the substrate concrete, such as the coefficient of thermal expansion, other properties should compensate for these differences for the repair to perform successfully; for example, a lower modulus of elasticity to reduce thermal stresses".

In this paper a compatibility model for patch repair is discussed. This model allows to determine if selected repair material is able to "cooperate" well with repaired concrete substrate in given conditions.

2 GENERAL APPROACH TO THE COMPATIBILITY SPACE MODEL

Material serviceability in construction is considered in light of the various requirements as defined by environmental service condition. These requirements determine the mathematical space of loads, including chemical, mechanical and other physical (mainly thermal) loads. N-dimensional compatibility space is created taking into account selected material control parameters.

Czarnecki et al. (1992) and Głodkowska (1994) have formulated three main compatibility models for: injection, patch repair and protective coating. Every model consists of a number of inequalities defining good compatibility requirements for selected repair systems. The material parameters proposed for evaluation of material compatibility for patch repair are presented in Table 1.

Table 1. Properties of repair material and concrete substrate used in a compatibility model of patch repair

Material property:	Repair material	Concrete substrate
tensile strength [MPa]	f_{tp}	f_{tc}
modulus of elasticity (in tension) [MPa]	E_{tp}	E_{tc}
modulus of elasticity (in compression) [MPa]	E_{cp}	E_{cc}
Coeff. of thermal expansion [1/K]	α_{Tp}	α_{Tc}
Coeff. of thermal conductivity [W/mK]	λ_{Tp}	λ_{Tc}
elongation at break [mm/mm]	ε_{tp}	-
curing shrinkage [mm/mm]	ε_s	-
Poisson coefficient [-]	ν_p	-
layer thickness [mm]	h_p	-
interlayer adhesion [MPa]	$f_{Ao}^{pi/(pi+1)}$	-
Max. crack width at coating failure [mm]	w_{max}	-
crack width [mm]	-	w_d
Crack width change [mm]	-	Δw
Adhesion to the substrate in shear [MPa]	f_{As}	
Adhesion to the substrate in tensile [MPa]	f_{Ao}	
Temperature gradient during service [K]	ΔT	

The requirements for good compatibility between repair material and concrete substrate are formulated using mathematical inequalities (see Table 2), where the variables are the material control parameters. The range of values for these parameters should be defined for the given repair type and the compatibility should be calculated over the whole domain of variability of the material control parameters. The range of material parameter values usually corresponds to that of existing repair materials. However, the compatibility space can be also determined for a "virtual" repair material, which may not exist yet. It means that the compatibility approach can be also used for designing new materials that result in a repair that has a proper equilibrium among reliability, durability and economy.

Table 2. Compatibility requirements for patch repair

Compatibility requirements	Remarks
$f_{tp}(t_o) \geq f_{tcm}(t_o)$ $f_{Ao}(t_o) \geq f_{tcm}(t_o)$, $f_{As}(t_o) \geq f_{tcm}(t_o)$	f_{tcm} (t_0) can be exchanged by eg. EN 1504 requirements: - 2.0 MPa (R4) or 1.5 MPa (R3) for structural repair - 0.8MPa (R2) for surface repair
$f_{tp_i}(t_o) \geq f_{As}^{p_i/(p_i+1)}(t_o)$, $f_{As}^{p_i/(p_i+1)}(t_o) \geq f_{tcm}(t_o)$	For multi-layer systems
$f_{As}(t_o) \geq \mathrm{C}$ and $f_{Ao}(t_o) \geq \mathrm{C}$, where $\mathrm{C} = \dfrac{\left(\varepsilon_{tp}(t_o) \cdot k_s - \dfrac{f_{tcm}(t_o)}{E_{tcm}(t_o)}\right) E_{tp}(t_o) \cdot E_{tcm}(t_o)}{E_{tp}(t_o) + E_{tcm}(t_o)}$	
$f_{As}(t_o) \geq \mathrm{D} \cdot \Delta\mathrm{T}$ and $f_{Ao}(t_o) \geq \mathrm{D} \cdot \Delta\mathrm{T}$, where $\mathrm{D} = \dfrac{(\alpha_{Tp} - \alpha_{Tc}) E_{tp}(t_o) \cdot E_{tcm}(t_o)}{E_{tp}(t_o) + E_{tcm}(t_o)}$	
$\dfrac{\lambda_{Tc}}{\lambda_{Tp}} < \dfrac{E_{tcm}(t_o) \cdot \alpha_{Tc}}{D}$,	For large-area repair; D as above
$\alpha_{Tp} \cdot E_{tp}(t_o) \leq 0{,}13 \cdot \ln(\dfrac{f_{c,cube}^{G}}{2{,}44})$	For polymeric materials only
$f_{tp}(t_o) \geq \dfrac{\psi_p \cdot E_{cp}(t_o) \cdot \varepsilon_s(t,t_o)}{(1-\nu_p)}$, $f_{Ao}(t_o) \geq \dfrac{\psi_p \cdot E_{cp}(t_o) \cdot \varepsilon_s(t,t_o)}{(1-\nu_p)}$, $f_{As}(t_o) \geq \dfrac{\psi_p \cdot E_{cp}(t_o) \cdot \varepsilon_s(t,t_o)}{(1-\nu_p)}$, $f_{As}^{pi/(pi+1)}(t_o) \geq \dfrac{\psi_p \cdot E_{cp}(t_o) \cdot \varepsilon_s(t,t_o)}{(1-\nu_p)}$	ψ_p- coeff. takes into account the inelastic part of the final shrinkage strain hardening composites PC and PCC; eg. ψ_p= 0.3 for polymer mortar

When the protective coating is used the compatibility between coating and substrate as well as repaired mortar should be also evaluated. In this case, besides of requirements given in Table 2, additional requirements towards a crack-bridging ability are particularly important. The requirements for crack-bridging ability are given in the standard EN1504-2. For determination of compatibility space for protective coating the requirements presented in Table 3 were used (Głodkowska 2003a).

Table 3. Requirements defining crack-bridging ability (Głodkowska 2003a)

Coating Type	Requirements for crack-bridging ability
High f_{tp} Low ε_{tp}, eg. epoxy coating	$\alpha \cdot [(2l_v \cdot \varepsilon_{tp}(t_o)) + (\frac{f_{tc} \cdot l_v^2}{2h_p \cdot E_{tp}(t_o)})] \geq w_d + \Delta w$ where: $l_v = \frac{f_{tp}(t_o) \cdot h_p}{f_{tc}}$ $\alpha = \frac{h_p}{w_{\max}} \cdot \frac{f_{tp}(t_o)}{E_{tp}(t_o)}$
Low f_{tp} High ε_{tp} Low E_{tp} eg. polymer – cement coating	$\alpha \cdot h_p \geq w_d + \Delta w$ α – as above

The mathematical inequalities are formulated using simplifying assumptions so that the compatibility model is sufficiently accurate yet simple enough to use. In the case of polymer repair materials, the common simplifying assumptions include: validity of elastic behavior for repair material, lack of synergistic effects of various loads, and service conditions below the glass transition temperature of the polymers used. The concrete substrate is assumed to be given and the proper repair system has to be selected for the given substrate and service loads.

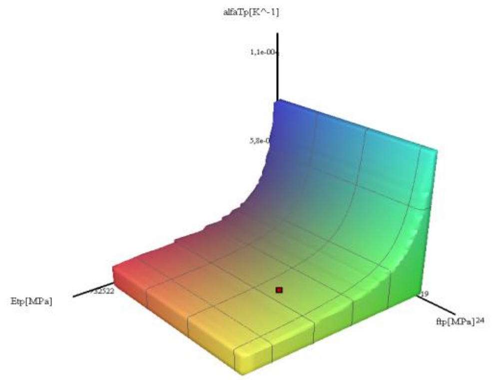
The concept of compatibility was successfully applied in further research projects (eg. Czarnecki et al. 2004, Garbacz & Głodkowska 2012). Based on large experimental program Głodkowska has proposed modifications of compatibility requirements taking into account long-term loads (Głodkowska 2011) as well as effect of coating weathering (Głodkowska & Staszewski 2007). The possibility of application of this approach for strengthening systems was showed by Garbacz et al. (2000). Recently, basic challenge for improvement of compatibility estimation accuracy is development of compatibility measure to take into account variability in technical properties of the both repair material and concrete substrate (Czarnecki & Runkiewicz 2005).

3 DETERMINATION OF COMPATIBILITY SPACE

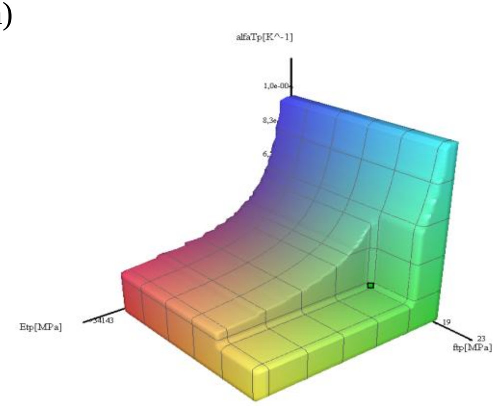
The models of compatibility space of repair material and concrete substrate, presented in chapter 2, are mathematically described by the set of suitable N-linear and non-linear inequalities. The technical properties of polymer composites and concrete substrate are their variables. Searching of compatibility space is focused on determination of the solution of the given set of inequalities (requirements of compatibility) by successively ascribing possible values (x1, x2, ..., xn) to the technical properties of repair materials and concrete substrates. The solution of the set of inequalities defines the N-dimensional compatibility space.

To determine compatibility space the suitable computer programs were developed at Koszalin University of Technology (Głodkowska 1994, Głodkowska 2003) and Warsaw University of Technology (Czarnecki et al. 1997). Currently, a new program ANCOMP for determination of compatibility space was developed (Garbacz 2013).

The Figure 1 presents the compatibility subspace determined for commercial polymer mortar used for repair of concrete substrate with characteristic compressive strength of 15 MPa. The temperature gradient during service was assumed to be 30K. The point corresponding to the mortar properties is located outside of compatibility space. The decrease of value of elasticity modules of repair mortar causes a larger compatibility space and mortar can fulfill requirements of compatibility.



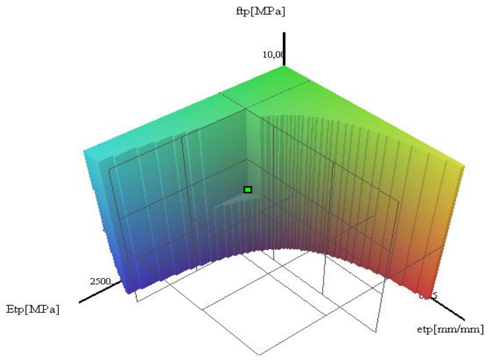
a)



b)

Figure 1. The examples of compatibility subspaces determined with ANCOMP program defined by elasticity modulus E_{tp}, tensile strength f_{tp} and coefficient of thermal expansion $alfa_{Tp}$: a) commercial polymer mortar with high E modulus (non-compatibility), b) commercial polymer mortar with lower E modulus (compatibility)

Figure 2 shows effect of crack presence on compatibility of elastic polymer-cement protective coating (Garbacz 2013) applied on cracked concrete substrate and non-cracked substrate (cracks will occur during service).



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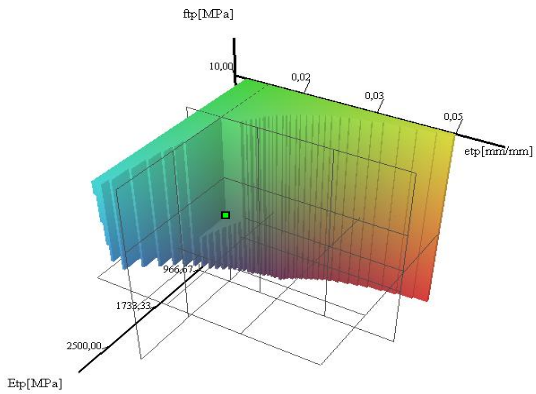

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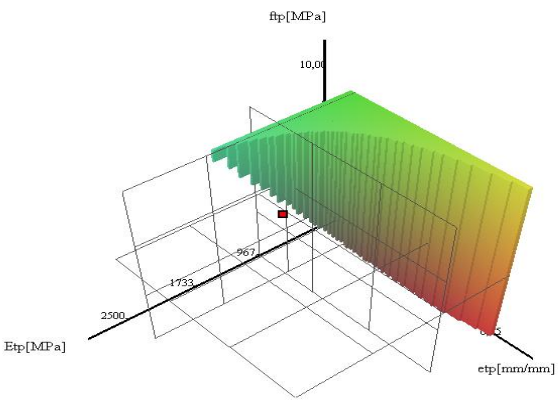


c)

Figure 2. The examples of compatibility subspaces determined with ANCOMP program defined modulus of elasticity E_{tp}, elongation at break, ε_{tp} and tensile strength f_{tp} showing effect of changes of crack width: a) w_d = 0,1mm on cracked substrate (compatibility), b) w_d = 0,1mm on non-cracked substrate (compatibility); c) w_d = 0,2mm on non-cracked substrate (non-compatibility); Δw = 0.03 mm in all cases

The compatibility requirements in the ANCOMP program can be modified very easy and can be used for analysis of compatibility issues in any multilayer system.

4 EXAMPLE OF APPLICATION OF COMPATYBILITY APROACH IN REPAIR

This chapter demonstrates usability of the compatibility approach in practice on the example of material selection for repair and protection of a reinforced concrete tanks in sewage plant (Głodkowska 2003b).

Both elements were produced as the monolithic members. The basic reason of concrete structures deterioration (Fig.3) was technological faults: too low depth of concrete cover, improper compaction of the concrete and a lack of protection against aggressive environment.

a) b)

Figure 3. General view of the damage of tank walls in: a) preliminary sedimentation tank, b) fermentation chamber

The results of assessment, including mechanical analysis, showed that technical state of tank is acceptable from mechanical point of view. The performed calculations indicated that crack with maximum width of 0.2 mm can appear in the tank wall. The project of repair and anticorrosion protection of this structures was proposed using compatibility models defined by requirements presented in Tables 2 and 3.

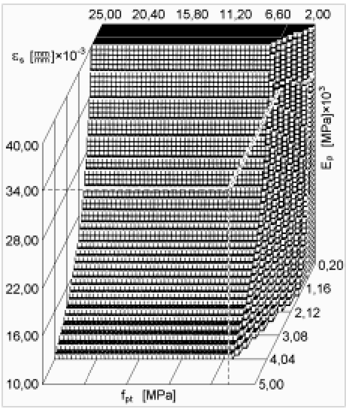
The commercially available fine-grained and course polymer-cement mortars were selected for surface and structural repair of wall and bottom plate. To ensure the tightness of the tanks application of sprayed elastic polymer coating was proposed. Table 4 presents, determined experimentally, selected properties of concrete substrate, mortars and coating used for repair.

Calculations (Fig.2), taking into account service conditions (concrete substrate properties, temperature gradient) indicated that selected materials should be compatible with repaired concrete substrate. After almost 25 years of service no visible deterioration is observed.

Table 4. Selected properties of repair mortars and protective coating used for calculation of compatibility space for repaired concrete structures

Property	Value
Concrete substrate	
f_{ctk} [MPa]	1.35
E_{ctm} [MPa]	13500
Polymer-cement mortar *)	
f_{tp} [MPa]	5.25 (4.80)
ε_{tp} [%]	0.028 (0.024)
E_{tp} [MPa]	17500 (18050)
f_{Ao} [MPa]	2.5 (2.0)
Elastic polymer-cement coating	
f_{tp} [MPa]	0.80
ε_{tp} [%]	18
E_{tp} [MPa]	500
f_{Ao} [MPa]	0.8

*) fine-grained and course mortar respectively



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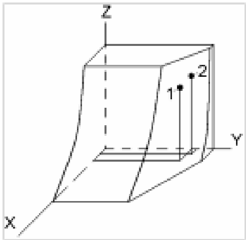
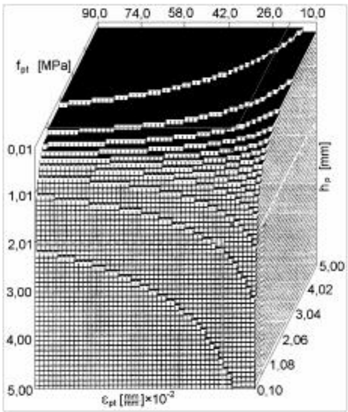


1- fine-grained mortar
2-course mortar



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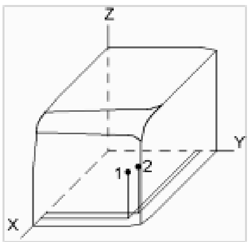

1- after repair
2- after 3 years of service

Figure 3. compatibility subspaces for commercial materials selected for repair: a) polymer-cement mortars used for structural and surface repair of concrete tanks and the points reflecting properties of polymer-cement mortars; b) protective coating the points reflecting properties of elastic polymer-cement coating

5 CONCLUSIONS

The presented results clearly demonstrate usability of the compatibility model for evaluation of requirements for a good cooperation between repair materials and concrete substrate. They also enable the prediction of behavior the system:-concrete repair material during service and an indication of the good cooperation that will not be met either at the stage of selection of repair and protective coating, or during the use of the building structure.

The usability of compatibility approach was confirm in practice during selection of repair mortar and protective coating for protection of concrete walls in the concrete sewage tanks. After 25 years of service the mortar and coating selected on the basis of compatibility approach are in good conditions and no deterioration is observed.

The program ANCOMP, using multi-criteria models of good cooperation shown in the article, may serve as a useful tool for the design of new composites for repair and protective coatings, meet the requirements of effective and durable repair of concrete.

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