QUANTITATIVE APPROACHES TO THE CONCRETE REPAIR COMPATIBILITY

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Abstract: Compatibility is considered as a basic rule for selection of repair materials and requires proper selection of material properties in respect to properties of concrete substrate. The compatibility concept has been formulated in the early nineties. One of the main challenges to be faced now lies in evaluating quantitatively compatibility and determining what it requires under given circumstances. In this paper compatibility index as a new approach to quantitative characterization of repair compatibility is presented. Additionaly, effect of environment on quantitative characterization od compatibility was discussed.

Keywords: concrete, durability, repair, compatibility, ring test, compatibility index

1. Introduction

In the field of civil engineering, repair and rehabilitation have drawn significant attention in the recent years [1]. Even though engineers have been repairing deteriorated structures for many years now, the rate of unsuccessful concrete repairs remains unacceptably high. Because of the lack of knowledge gained on the influence of certain fundamental parameters, the achievement of durable repairs is reduced in some circumstances to merely a „hit or miss" process.

The aim of concrete repairs is to prolong the useful service life of an existing structure, to restore its load-carrying capacity and stiffness, and/or to strengthen its members. Compatibility is considered as a basic rule for selection of repair materials and requires proper selection of material properties in respect to properties of concrete substrate [2]. The compatibility concept has been formulated in the early nineties [3,4]. It covers four types of compatibilities: dimensional, permeability, chemical, electrochemical. Recently, the understanding for compatibility requirements in repair system is demonstrated in many papers. This approach can be also found in the ACI Concrete Repair Manual as well as well in new European Standard EN 1504. The level of compatibility will generally determine whether a repair project is a success or a failure, and whether or not a repaired structure is durable. A prerequisite to achieve adequate composite action is lasting bond between the existing substrate and the newly-cast material [5]. Recently, compatibility issues in design and implementation of concrete repairs and overlays approach were summarized by Vaysburd et al. [6]. In the paper two approaches for quantitative description of compatibility are presented applied to cement and polmer based repair materials.

One of the main challenges to be faced now lies in evaluating quantitatively compatibility and determining what it requires under given circumstances (characteristics of the structure to be repaired and the environment). For the compatibility approach to become accessible to the industry, simple and reliable characterization tests are needed. Various test procedures (ring test, beam curling test, box test) have been developed in recent years for the evaluation of the cracking sensitivity of repair materials [7]. Some of those so-called performance tests could become key tools for the identification of performance criteria, provided that clear relationships with both the basic material properties and the composite repair behaviour are established.

In the present paper, two approaches for quantitative evaluation of repair compatibility are presented. The first one, based on a simple restrained shrinkage test procedure and the calculation of a compatibility index, provides an interesting mean to evaluate the shrinkage cracking sensitivity of repair materials. The other approach addressed herein uses basic material properties, most of which can be generated rather easily, to calculate so-called compatibility space. As far as the properties of interest lie within the ranges of values enclosed by the space, compatibility can be achieved. The approach is well suited to evaluate for instance dimensional compatibility of polymer-based repair systems subjected to temperature variations over the service life of the repaired element.

2. Compatibility index evaluation based on the restrained-shrinkage ring test

Restrained-shrinkage ring test

This paper presents the results of the large project on the quantitative relationship between the individual dimensional compatibility-related properties (notably elastic properties, creep, drying shrinkage) and the corresponding stress and strain values recorded in an annular restrained shrinkage test, commonly referred to as the ring test (Fig.1).

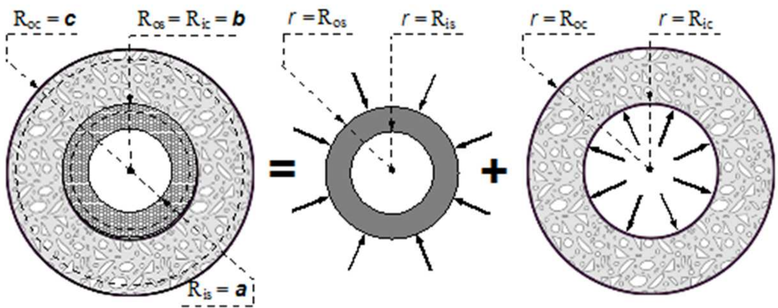


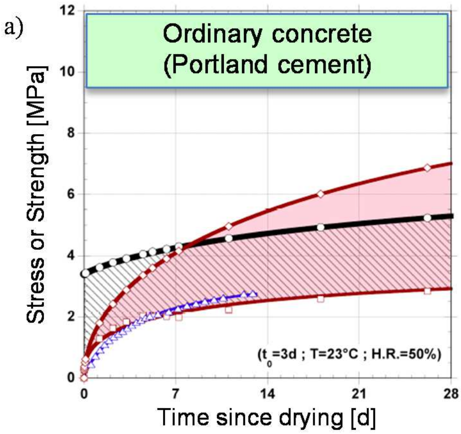
Fig. 1. Basic analysis of the restrained shrinkage test specimen (mechanical equilibrium) and geometrical parameters

While the actual deformation and stress gradients across the thickness of the specimens are considered in the calculations, the analysis of the results is based on the average stresses. The evolution of the average shrinkage-induced stress ($\sigma_{c\ avg.}$) over time can be calculated with equation 1, where ε_{fs} is the concrete free shrinkage, E_c and E_s are the elastic moduli of concrete and steel, ϕ_c is the creep coefficient of concrete, ν_c and ν_s are the *Poisson's* ratios of concrete and steel, and *a*, *b*, and *c*, are the internal, interfacial and external radii of the composite steel-concrete ring specimen:

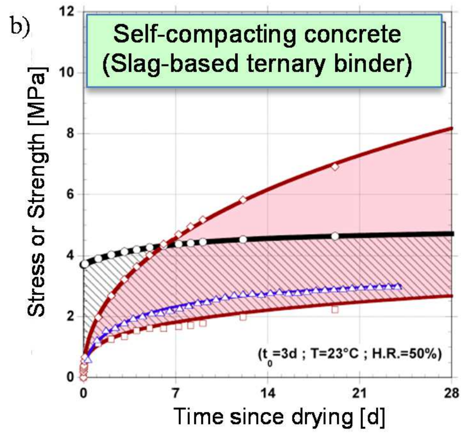
$$\sigma_{c\ avg.}(t) = \frac{b(b+c)}{c^2 - b^2} \frac{\varepsilon_{fs}(t)}{\left[\frac{1}{E_s}\left(\frac{b^2+a^2}{b^2-a^2}+\nu_s\right)+\frac{1+\phi_c(t)}{E_c(t)}\left(\frac{b^2+c^2}{c^2-b^2}-\nu_c\right)\right]} \tag{1}$$

By comparing the ring test results with the calculated tensile stresses, the validity and accuracy of the theoretical approach could be appraised.

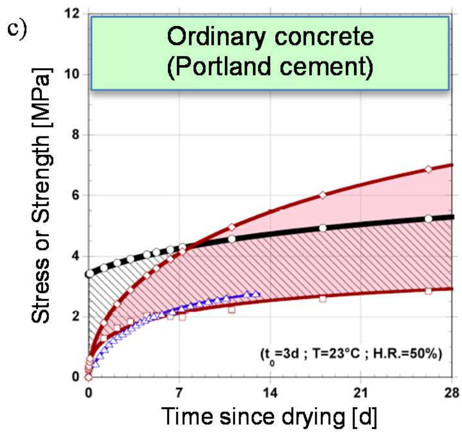
Figure 2 shows ring test results obtained for an ordinary repair concrete (OPC), together with two self-compacting repair concrete mixtures produced with a slag-based ternary binder (SCC-ST) and a fly-ash-based ternary binder (SCC-FT) respectively. On each diagram, the calculated theoretical stress evolution with and without stress relaxation (lower and upper solid red lines respectively) and the experimental stress recorded over time in the ring test (solid blue line) are presented together with the corresponding tensile strength evolution curve (black line).



reference repair concrete (OPC)



self-compacting repair concrete (SCC-ST)



self-compacting repair concrete (SCC-FT)

Fig.2. Comparative development of recorded and theoretical tensile stresses in AASHTO PP34 ring test specimens exposed to drying at 50 % R.H. at the age of 3 days (note: solid blue line: stress recorded in the ring; lower and upper solid red lines: theoretical average concrete stress, with and without stress relaxation respectively; solid black line: tensile strength of the concrete)

The pink areas between the red lines on the graphs of Figure 2 correspond to the theoretical stress relaxation potential of the concrete. By comparing the shaded areas in the two diagrams (= area between the tensile strength curve and the lower red line), it can be concluded that the OPC and SCC-ST mixtures are much less sensitive to shrinkage cracking than the SCC-FT mixture. In fact, in diagram c), both the theoretical tensile stress (including relaxation) and the recorded stress curves reach or get close to the tensile strength curve quite rapidly, whereas in diagrams a) and b), the recorded stress remains much lower, coinciding more or less with the relaxed stress curves.

Overall, a good correlation was found between the ring test results and the tensile stress values calculated based on individual concrete properties / phenomena. The level of correlation was particularly high when the test specimens (beams, rings) were partially sealed such as to obtain the same drying surface / volume ratio (S/V) in the various experiments. Based on the collected data and observations, it can be asserted that the calculation method that was developed provides a good basis for analyzing quantitatively the dimensional compatibility of repair materials.

Compatibility index calculation

Classical formulas derived for thick cylindrical specimens were used to analyze the tensile stress buildup in restrained shrinkage test specimens. A quantitative approach for the evaluation of concrete repair with a single dimensional compatibility parameter, the compatibility index, was then developed. Compatibility index evolution curves were finally calculated for a range of repair concrete mixtures in order to validate the approach and highlight material behavior relating to composition parameters and temperature. The dimensional compatibility index can be expressed in terms of deformation, thus allowing to relate explicitly to the various individual properties and phenomena involved in the material's response in restrained shrinkage conditions (strength, elastic modulus, creep, drying shrinkage), as well as to the degree of restriction of the element. For the latter, constants are calculated, based upon the respective geometry and mechanical properties (Poisson's ratio) of both the restraining device and the test specimen.

The time-dependent expression takes the following general form, where f_t is the concrete tensile strength, α_r is the instantaneous elastic degree of restraint, and α'_r is the creep-dependent restraint:

$$C.I.\,(t) = \frac{\left[\dfrac{f_t(t)}{E_c(t)} + \phi_c(t)\varepsilon_{fs}(t)\alpha_r(t)\cdot\dfrac{C_c}{C_g}\alpha'_r(t)\right]}{\varepsilon_{fs}(t)\alpha_r(t)} \qquad (2)$$

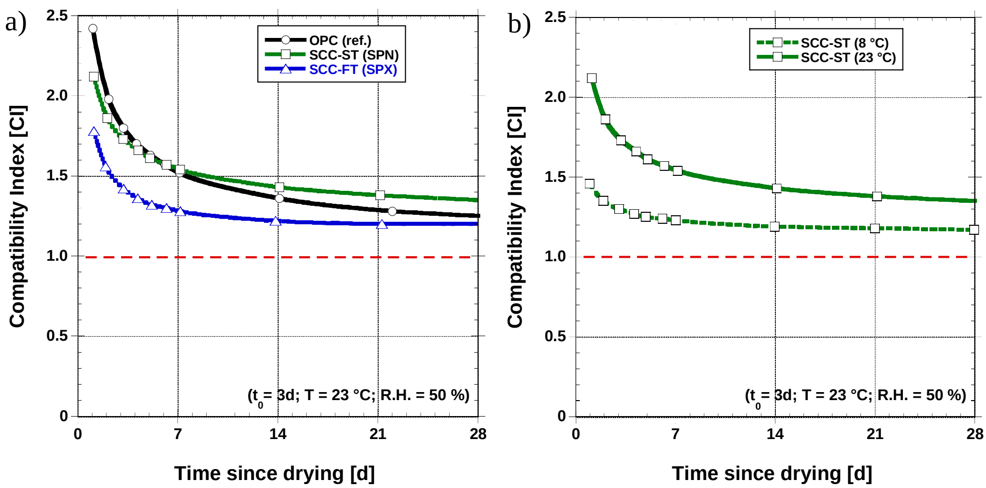
$$C_g = \frac{b(b+c)}{c^2 - b^2} \qquad C_c = \frac{b^2+c^2}{c^2-b^2} - \nu_c \qquad C_s = \frac{b^2+a^2}{b^2-a^2} + \nu_s$$

$$\alpha_r(t) = \frac{C_g}{\left(\dfrac{C_s}{E_s} + \dfrac{C_c}{E_c(t)}\right)E_c(t)} \qquad \alpha'_r(t) = \frac{C_g}{\left(\dfrac{C_s}{E_s} + \dfrac{C_c\left(1+\phi_c(t)\right)}{E_c(t)}\right)E_c(t)}$$

As it requires the evaluation of individual properties that for most are readily available (i.e. strength, elastic modulus, and drying shrinkage), the *compatibility index* carries much potential as a relatively simple and convenient analytical tool for assessing the cracking potential of concrete repair materials.

The CI parameter can alternatively be expressed in terms of stress. The compatibility index is then calculated as the ratio between the sum of the tensile strength (f_t) and total stress relaxation ($\Delta\sigma_{relaxation}$) in given restraining conditions, and the averaged elastic stress ($\sigma_{elastic}$) induced by restrained drying shrinkage.

The diagram presented in Figure 3 a) shows the evolution of this index for the same three concrete mixtures tested in the ring experiments (Fig. 2). Typically high at early age, the CI value is observed to decrease gradually with the ageing process, with quite steep decreasing rates in the first few days. During the drying period considered (0 to 28 d), the CI values of the shrinkage-compensating (SCC) mixture produced with a slag-based ternary binder and the reference ordinary concrete (OPC) mixture are significantly higher than those determined for the fly-ash-based SCC mixture, especially in the first two weeks of drying. In other words, the two former mixtures seem to exhibit much more early-age dimensional compatibility than the SCC-TF repair mixture. The ring test stress development curves on the diagrams of Figure 2 show good agreement with the trends revealed by the CI curves. As a matter of fact, the rapid increase in tensile stress recorded for the SCC-FT rings is consistent with the much steeper decreasing rate of the CI value observed in the graphs of Figure 3 a).



reference repair concrete (OPC) self-compacting repair concrete mixtures (SCC-ST, SCC-FT) exposed at 23°C

self-compacting repair concrete mixtures SCC-ST exposed at different temperatures

Fig. 3. Evolution of the compatibility index (CI value) with time calculated fron ring test specimens exposed to drying at 50 % R.H. at the age of 3 days

Influence of environmental conditions on the compatibility index

The compatibility between repair material and concrete substrate also depends on environmental conditions during application of material and service of repaired construction.

As already indicated, the CI curves can be used to compare the compatibility of different concrete mixtures and to identify specific material tendencies. In a recent investigation by Modjabi-Sangnier [7], the comparison of results for a range of repair mixtures and curing conditions has shown that dimensional compatibility is very sensitive to certain composition variables and to temperature in the early stages of hydration. For instance, test results generated in this study remarkably show that a given binder / plasticizer agent combination can yield quite different conclusions depending on the curing temperatures. While some combinations exhibit more interesting characteristics at low curing temperatures with respect to compatibility and the cracking risk, others show exactly the opposite, as shown on the graph of Figure 3 b).

3. Compatibility modelling approach applied to polymer-based materials

Influence of temperature upon polymer-based repair materials

In comparison with cement-based repair materials, polymer-based materials are sensitive to temperature both at the time of application and during their service life, owing to their typically much larger coefficient of thermal expansion. Application guidelines and requirements are usually well described in technical data sheets. While the properties and characteristics presented in the latter are generally determined at room temperature, they can actually vary considerably with the temperature fluctuations.

An example of such is provided in Figure 4, which shows results of extensive direct tensile experiments conducted on two commercial polymer coatings (epoxy EP and polyurethane PU) intended for industrial flooring use [8]. The experiments were carried out at different temperatures (-20, 0, 20, 40 and 60°C) using a testing machine equipped with a special thermal conditioning chamber. The results obtained for indicate that test temperature does not exert the same influence on epoxy and polyurethane. As shown in Figure 6, the tested polyurethane material exhibits sharp decreases in tensile strength and modulus of elasticity when increasing the temperature from the from subzero range. Tensile strength and modulus of elasticity of the tested epoxy-based floor coating also decrease as the temperature increases, but much more gradually, at leat up to 20°C. Recorded elongation values (maximum strain recorded at failure) increase with temperature in a monotonic fashion in the case of epoxy, whereas for polyurethane, it apparently reaches a maximum value around 20°C, beyond which it decreases almost linearly.

Influence of temperature upon polymer-based repair materials

To analyze quantitatively the effect of temperature upon compatibility of polymer-based repair systems, a modeling approach proposed by Czarnecki et al. [3] was used. They have proposed three main compatibility models for injection, patch repair and protective coating respectively (Table 1). Each model consists of a series of inequalities defining specific compatibility requirements to be fulfilled for selected repair systems. In this way N-dimensional compatibility space is created. To determine compatibility space, where all requirements are fulfilled simultaneously, the suitable computer programs were developed [9–10]. They allow for graphical presentation of a 3D compatibility subspaces defined by selected material properties. 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.

A review of the compatibility requirements and related variables laid out in Table 1 clearly indicates that in the case of polymer-based materials, most of them are in fact sensitive to service temperature.

Figure 5 presents the examples of compatibility subspaces determined for the two aforementioned polymer-based coating applied on a concrete substrate having the same concrete substrate characteristics, i.e. mechanical and thermal properties, crack width and temperature gradient (see Table 1).

Table 1. Basic requirements for compatibility between of repair material – concrete substrate [3]

<table>
<tr><th>Requirements of compatibility</th><th>Injection</th><th>Patch repair</th><th>Coating</th><th>Symbols</th></tr>
<tr><td>$\varepsilon_{tp} \cdot s_r \geq \Delta w$</td><td>+[1]</td><td>+[2] for $l_u \geq l_f$</td><td>+</td><td rowspan="8">f_{tp}, f_{tc} – tensile strength [MPa]
E_{tp}, E_{tc} – modulus of elasticity (in tension) [MPa]
E_{cp}, E_{cc} – modulus of elasticity (in compression) [MPa]
T_p, T_c – coeff. of thermal expansion [1/°C]
λ_{Tp}, λ_{Tc} – coeff. of thermal conductivity [W/m°C]
ε_{tp} – elongation at break [mm/mm]
ε_s – curing shrinkage [mm/mm]
ν_p – Poisson coefficient [-]
h_p – layer thickness [mm]
w_{max} – max. crack width at failure [mm]
Δw – crack width change [mm]
f_{As} – adhesion to the substrate in shear [MPa]
f_{Ao} – Adhesion to the substrate in tensile; pull-off strength [MPa]
ΔT – temperature gradient during service [°C]
p – repair material c – concrete substrate</td></tr>
<tr><td>$\frac{f_{tp} \cdot h_p}{f_{tc}} \cdot \varepsilon_{tp}(1+\varepsilon_{tp}) \geq \Delta w$
$\frac{f_{tp} \cdot h_p}{f_{tc}} \cdot \varepsilon_{tp}(1+\varepsilon_{tp}) \geq w_{\max} + \Delta w$</td><td>-
-</td><td>+[2]
+[3]</td><td>+[2]
+[3]</td></tr>
<tr><td>$f_{Ao} \geq f_{tc}$
$f_{As} \geq f_{tc}$</td><td>- +</td><td>+ +</td><td>+ -</td></tr>
<tr><td>$f_{As} > \frac{(\alpha_{Tp} - \alpha_{Tc})}{E_{tp} + E_{tc}} \frac{E_{tp} \cdot E_{tc}}{} \cdot \Delta T$</td><td>+</td><td>+</td><td>+</td></tr>
<tr><td>$f_{As} \geq \frac{\left(\varepsilon_{tp-} \frac{f_{tc}}{E_{tc}}\right)}{E_{tp} + E_{tc}} E_{tp} \cdot E_{tc}$</td><td>+[4]</td><td>+</td><td>+</td></tr>
<tr><td>$\frac{\lambda_c}{\lambda_p} < \frac{E_{tp} \cdot \alpha_{Tc}}{B}$
$B = \frac{(\alpha_{Tp} - \alpha_{Tc})}{E_{tp} + E_{tc}} E_{tp} \cdot E_{tc}$</td><td>-</td><td>-</td><td>+</td></tr>
<tr><td>$f_{tp} \geq \frac{0{,}3 \cdot E_p \cdot \varepsilon_s}{(1-\nu_p)}$
$f_{Ao}^{p/b3)} \geq \frac{0{,}3 \cdot E_p \cdot \varepsilon_s}{(1-\nu_p)}$
$f_{Ao}^{pi/pi+1} \geq \frac{0{,}3 \cdot E_p \cdot \varepsilon_s}{(1-\nu_p)}$</td><td>+
+
-</td><td>+
+
+</td><td>+
+
+</td></tr>
<tr><td>$h_p \geq \pi\sqrt{D \cdot t}$</td><td>-</td><td>-</td><td>+</td></tr>
</table>

+ condition that determines the compatibility of polymer composite with cement concrete, - the condition does not occur,[1] in this case: $l_f = a_r$,[2] in regard to the cracked concrete surface,[3] in regard to the non-cracked concrete surface,[4] in case of cracks injection $f_{tp}^{p/b}$ is used

The calculations were performed using the computer program ANCOMP, developed at the Warsaw University of Technology.To determine compatibility space at different service temperatures, the values of properties yielded in the tensile experiments were used in evaluating the specific compatibility requirements presented in Table 1. Results of the simulations show that temperature changes during service of polymer coating can significantly affect the potential or ability of a given polymer-based repair material to fulfill the requirements for compatibility on a given existing concrete substrate because of the corresponding changes in mechanical properties. The effect of temperature upon properties of EP and PU coatings translated into significant differences in compitability space ranges.

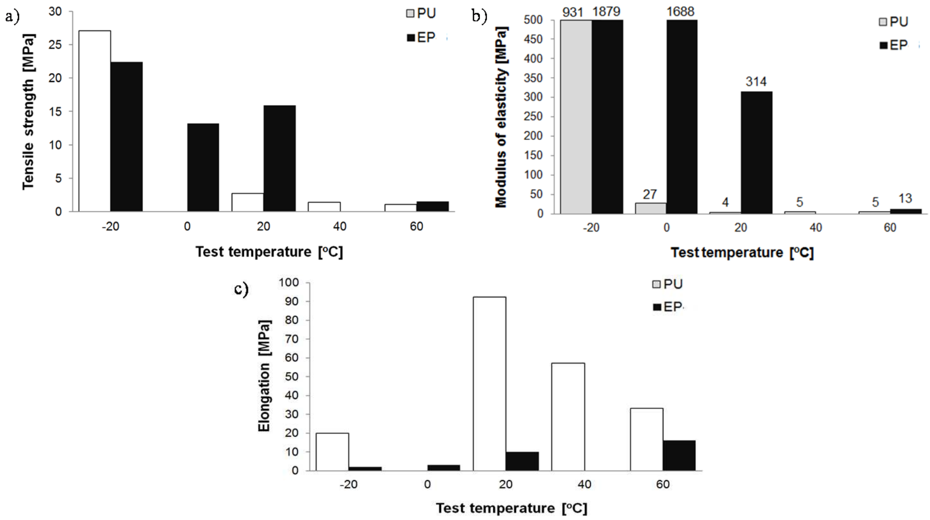


Fig. 4. Influence of ambient temperature upon a) tensile strength, b) modulus of elasticity, and c) elongation for polyurethane-based (PU) and epoxy-based (EP) coatings (test parameters: temperatures of -20, 0, 20, 40 and 60°C; deformation rate of 50 mm/min) – acc. to [8]

Temp Polyurethane-based (EP) industrial floor coating Epoxy-based (PU) industrial floor coating

-10°C

+20°C

+60°C

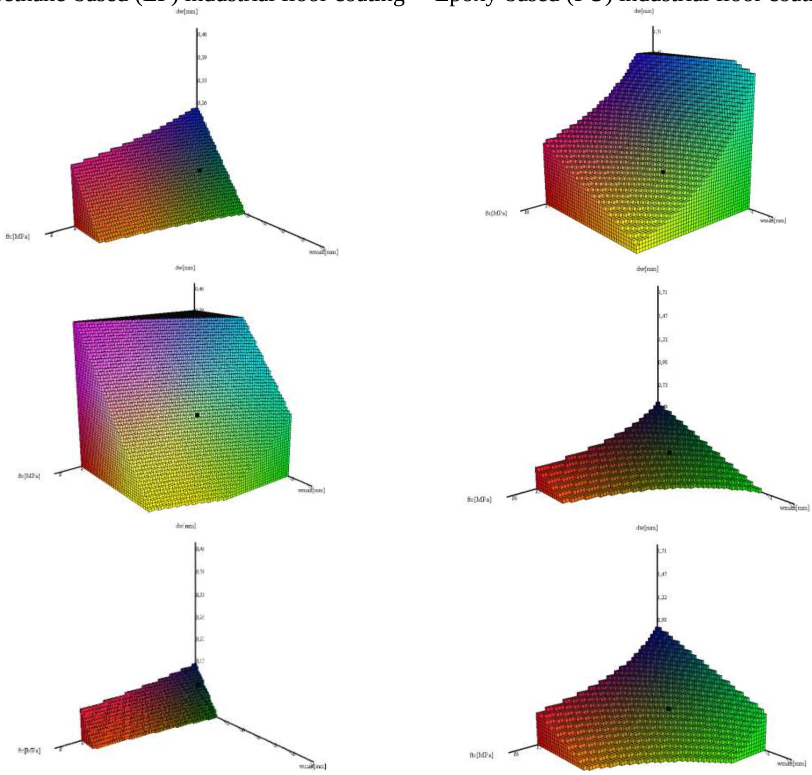


Fig. 5. The examples of compatibility subspaces, determined with ANCOMP program for epoxy (EP) and polyuretane (PU) coatings at different service temperatures, defined by compressive strength of concrete f_{tc}, maximum crack width w_{max} and crack width changes Δ_w

4. Conclusions

The proposed compatibility index appears as a quite promising analytical tool for predicting the performance of repair materials in terms of shrinkage-cracking resistance. Compatibility index data were determined for a range of repair materials and confronted with ring test results. The comparison showed good correlation, the mixture classification determined on the basis of *compatibility index* calculations being consistent with the classification based on the shrinkage-induced stresses recorded experimentally.

Compatibility spaces also appear as quite valuable tool for qualifying repair materials in terms of dimensional compatibility. especially as it allows to address rather easily the variability considerations (material properties, exposure conditions).

The compatibility complimentary approaches presented in this paper provide a sound basis for the identification of dimensional compatibility criteria. Such performance criteria are much awaited in the repair industry, to assist both the development of crack-resistant materials and the issuance of improved materials specifications.

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INDEKS KOMPATYBILNOŚCI – NOWE ILOŚCIOWE PODEJŚCIE KOMPATYBILNOŚCI NAPRAW BETONU

Streszczenie: Kompatybilność jest uważana za podstawową zasadę doboru materiałów do napraw w zależności od naprawianego podłoża betonowego. Koncepcja kompatybilności została sformułowana w latach 90-tych. Jednym z największych wyzwań jest możliwość ilościowej kompatybilności i określenia co jest wymagane, aby została ona zapewniona w danych warunkach. W artykule został zaprezentowany indeks kompatybilności jako nowe podejście do ilościowego charakteryzowania kompatybilności napraw. Dodatkowo, pokazano wpływ środowiska podczas stosowania i użytkowania na kompatybilność naprawy w przypadku kompozytów cementowych i polimerowych.

Słowa kluczowe: beton, trwałość, naprawa, kompatybilność, indeks kompatybilności, model przestrzeni kompatybilności