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Specifying Concrete Repair Materials

Specyfikacja materiałów do napraw betonu

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Abstract. Specification of materials for concrete repair is a complex task requiring broad knowledge of materials science, engineering and construction practice. In this paper, several issues important for proper design and implementation of concrete repair are discussed. It is stressed that the specification documentation is not a formality, but rather a critically important engineering step in view of fulfilling the durability and service life requirements.

Keywords: concrete repair, repair design, materials specification, compatibility factors.

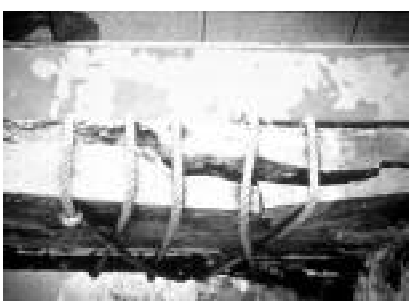
Streszczenie. Specyfikacja materiałów do napraw konstrukcji betonowych jest złożonym zadaniem wymagającym rozległej wiedzy z zakresu podstaw naukowych, inżynierskich oraz doświadczeń praktycznych. W artykule przedyskutowano wiele zagadnień istotnych przy przygotowaniu projektu naprawy konstrukcji betonowej i jego wdrożeniu. Podkreślono, że specyfikacja materiałów jest nie tylko formalnością, ale stanowi szczególnie istotne wytyczne inżynierskie pozwalające na spełnienie wymagań trwałości.

Słowa kluczowe: naprawa betonu, projekt naprawy, specyfikacja materiałów, rodzaje kompatybilności.

Good concrete repair is not a bandage ”fix” (Photo) for a structure in trouble – rather, it is a complex system that consists of numerous engineering tasks (Fig. 1). Designing and specifying concrete repair has unique needs differing from new construction. Therefore, the specifications must serve as action plans or roadmaps for the project's engineer, contractor, and quality controller.

Unfortunately, when it comes to the durability of repaired concrete structures, project documentation is not always adequate. For example, one shortcoming constantly repeated in specifications is the frequent reference to the ”direction” of the engineer or architect. The authors came across a specification concerning a material for an industrial plant repair project that simply read: *„The patch repair material's durability shall be as directed by the engineer.”*

The subjective character of such specifications can make bidding sound impossible. Additionally, such references are useless because they stem from either not knowing what should be required, or from a refusal to make an effort to study and analyze the issue to determine a specifica-



Extreme situation illustrating the need for repair engineering design and specifications (courtesy of the Structural Group, Columbia (MD), USA)
Skrajny przypadek ilustrujący konieczność przygotowania projektu i specyfikacji materiałów (dzięki uprzejmości Structural Group, Columbia (MD), USA)

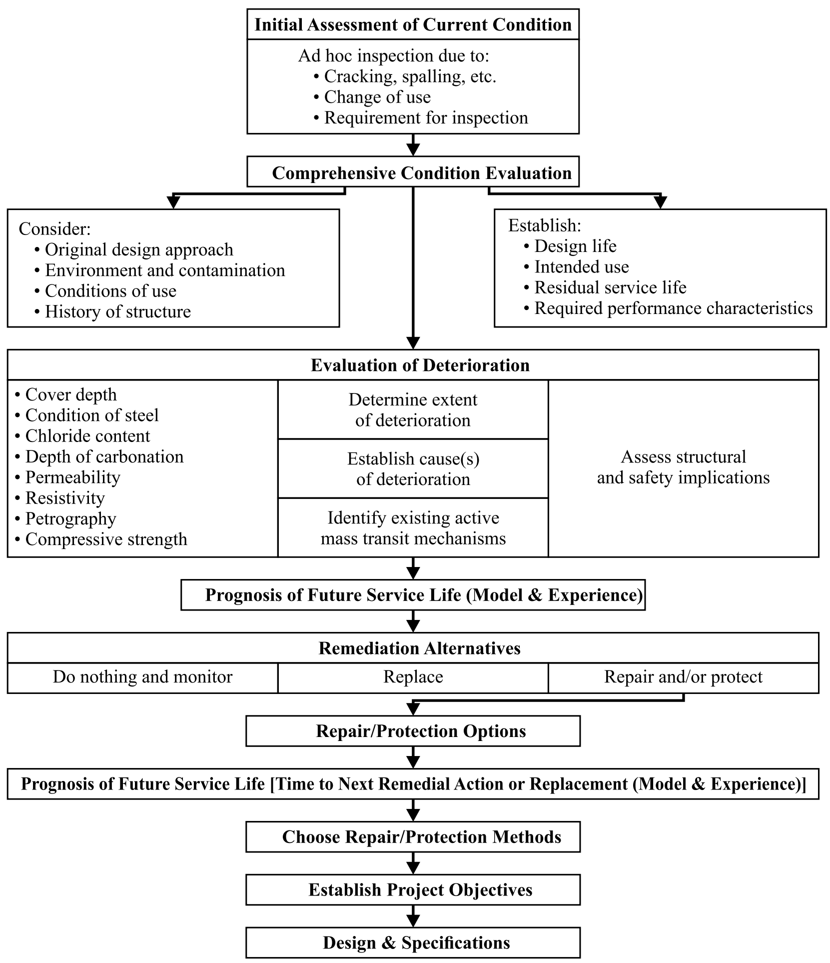


Fig. 1. Flowchart of concrete repair project design [6]
Rys. 1. Schemat blokowy projektu napraw konstrukcji betonowej [6]

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tion. It is an unfortunate fact some ”directing” engineers can be literal to a degree the specifier never intended.

Many specifications for repairs are a mixture of referenced standards and ”cut-and--paste” clauses from previous projects, recycled with little thought. Achieving durability should be found in carefully considered specifications for a particular project. However, this does not appear to be the case – widespread durability problems have led to extensive repair of previous repairs and, in some cases, eventual replacement of structural members.

Durability considerations

There are several durability-related factors playing into concrete repair specifications.

Compressive strength. There is a common misconception that higher-strength cement-based materials are necessary in severe environments for enhanced durability. However, this way of thinking does not take into account the realization a stronger and stiffer material is more likely to crack because the higher modulus of elasticity increases the tensile stress arising from shrinkage and other restrained volume changes.

Unfortunately, many specifiers blindly opt for so-called high-strength (i.e. ”high--performance”) cementitious materials containing ingredients such as silica fume or high-range water-reducing admixtures (HWRAs), which can also have negative side effects on performance of repair materials. While useful in certain applications, some components can also have negative side effects when it comes to using them for repair work. The terms ”high-performance” and ”high-strength” are often used as synonyms. However, high compressive strength is not an indication of improved durability and performance – in fact, the increase in strength may be gained at the expense of durability.

In reviewing 120 North American projects, the authors could not find a specification for a repair material with a compressive strength of approximately 20 MPa (3000 psi), even when the strength of the existing substrate was of such magnitude. The rationale seems to be the belief a 55 MPa (8000-psi) ”high-performance” material will always be more crack-resistant and achieve better durability.

The major fault of any material is not a matter of strength or stiffness, but rather a lack of resistance to crack initiation and propagation. The Victorians had high--strength cast iron, but its brittleness led to many failures. They soon realized ductility was the essence of safe structures and began using lower strength, ductile mild steel. In many cases, it makes sense to follow their lead and pay more attention to deformability and crack resistance of cementitious repair materials.

Another critical problem in many specifications is the oftenunjustifiable requirement for high early-strength repair materials. This may be necessary for some special applications, but for typical repairs it creates a greater potential for higher shrinkage and cracking. Long-term durability is primarily achieved by dimensional stability, not by high early-strength. Accelerated gain in strength generally comes with more self-stress from drying shrinkage, autogenous shrinkage, and thermal contraction. The rate of strength gain, in addition to the total degree of hydration, has a significant effect on cementitious materials’, pore structure, micro- and macro-cracking, and transport (i.e. permeability) properties.

Accelerated strength gain is also known to result in lower ultimate strength. However, the effect on durability is most generally overlooked. At a ”normal” rate of strength gain (i.e. three days for 50 per cent ultimate strength, seven days for 70 per cent, or 28 days for 100 per cent), hydration products have sufficient time to diffuse throughout the cement matrix and precipitate uniformly. At accelerated rates, hydration is so much faster than the diffusion process that most products remain static near the cement grains, leaving the interstitial space relatively open.

These relatively dense deposits of hydration products surrounding (and sometimes encapsulating) the cement grain serve as diffusion obstacles to water and hydration products. Therefore, further hydration is hindered, producing a much more open pore structure than that of comparable materials with a normal rate of hydration. Hence, strength gain acceleration in cementitious materials generally has a negative effect on their transport properties.

Based on this analysis, it can be concluded that for concrete and other cementitious materials – especially those exposed to severe environments – the rate of strength gain is critical to durability. Materials with slow strength gain (e.g. those containing fly ash or slag) might perform more satisfactorily under these conditions.

Repair materials with acceptable minimum early-strength properties should be used. If practical, their compressive strength should be specified at a stage later than the traditional 28 days. It should not be in excess of what is necessary for load-carrying purposes. The ”specified” strength valuesshould be kept at levels similar to theactual ”in-place” compressive strengths.

Cement and aggregates. When ready-mixed concrete is specified as a repair material, the ”more-cement-is-better” rule tends to wrongly prevail. Any attempt to produce durable cement-based material comes up against a dilemma. If a small amount of cement is added, the material is relatively crack-resistant, but permeable. If a large amount of cement is mixed into the concrete, the material becomes stronger and more impermeable, but less crack-resistant. In fact, if cement is added until extremely low permeability is achieved, the material becomes more brittle and has much less creep relaxation to sustain high tensile stresses induced by drying and autogenous shrinkage. In other words, it is impermeable between the cracks, but in the end, its true permeability can become substantially higher than the lower-strength material.

Therefore, durability cannot practically be achieved between the extremes of either too little or too much cement. One of the main reasons for more extensive cracking and the reduced durability of ”high-performance” concrete and other cementitious materials is these materials have higher cement contents, higher paste volumes, higher moduli of elasticity, and lower creep.

The specifications reviewed by the authors followed standard material manufacturers recommendations, such as the need for incorporating aggregates in thicker repairs: ”*When thickness of the repair exceeds 50 mm (2 in.), the repair mortar should be extended with 10 mm (3/8-in.) coarse aggregate.”*

The specifications also require the same aggregate quantity be used, regardless of the material composition and repair specifics (e.g. thickness, spacing of reinforcing steel, and clearance from reinforcement to the bottom of repair cavity). A crack-resistant, ”durable” repair material should not have a deficiency of any aggregate particle size. The adequate aggregate size distribution minimizes void content, as the incrementally small particles fill these spaces. The goal is to pack as much aggregate into the material mixture as practically possible, thereby reducing the amount of paste needed to fill the voids between particles.

Drying shrinkage. Drying shrinkage of a concrete repair material is one of the major factors influencing the overall repair durability. However, not a single limitation for shrinkage was found in the specifications of concrete as a repair material in the cases studied. Pre-packaged repair materials may be limited to certain shrinkage values, but without any indication to what age of the material and test conditions this is to be applied, such requirements are useless.

Of equal concern is the current myth that specifying low water-to-cementitious materials (w/cm) ratios reduces shrinkage. A low w/cm ratio may increase strength and density, but it is unlikely to reduce ultimate shrinkage (i.e. self-desiccation shrinkage and drying shrinkage). For given constituents, it is not the w/c ratio, but the total water and paste content of the mixture that has the greatest influence on the material's shrinkage and cracking potential [3].

Cement paste acts as a binder, filler, and finishing aid. However, it is also the phase undergoing shrinkage in concrete. Unrestrained neat cement paste can shrink four to five times more than concrete prepared with the same paste. Therefore, any reduction in paste quantity will make the greatest contribution to reducing shrinkage and cracking, along with improving durability (as far as adequate consolidation can be achieved).

Often, ''high-performance'' concrete with a w/cm ratio of about 0.25 is unnecessarily specified. In so doing, designers unintentionally create an epidemic outbreak of self-desiccation and cracking. Water-reducing admixtures are quite effective in modifying some concrete properties, but they may not necessarily reduce the amount of shrinkage. Sometimes, the opposite is true.

Unfortunately, it appears ASTM C494, *Standard Specification for Chemical Admixtures in Concrete* – which allows 35 per cent more shrinkage in test specimens with the admixture than that of control specimens – is too often disregarded. This means using low w/c and WRAs to keep the necessary workability may not always result in the expected shrinkage decrease. Instead, it can actually end up causing an increase in shrinkage and result in cracking.

Specifications that unintentionally increase the shrinkage can lead the concrete to experience severe cracking. Table 1 summarizes some of the material properties critical for a low-cracking, durable material.

Table 1 – Cement-based repair material's sensitivity to cracking control parameters [7]

Tabela 1. Parametry wpływające na podatność cementowych materiałów naprawczych na pękanie [7]

Parameter	Effect		
	Major	Moderate	Minor
Drying shrinkage	X		
Modulus of elasticity	X		
Creep		X	
Compressive strength	X		
Early strength	X		
Paste content	X		
Cement content and type	X		
Aggregate content, type and size	X		
Coefficient of thermal expansion			X
Water to cementitious materials ratio			X
Accelerating admixtures	X		
Plasticizers		X	
Silica fume	X		
Fly ash		X	
Slag		X	
Water content	X		
Slump (within typical ranges)			X

Permeability. One of the fundamental factors influencing the initiation and the extent of damage to reinforced concrete is its permeation characteristics. The movement of moisture – which can contain aggressive agents – is fundamental to the repaired structure's durability. This transport mechanism can produce detrimental physical, chemical, and electro-chemical effects.

Specification of chloride permeability limits based on ASTM C1202, *Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, is a regular practice in North America, and almost all specifications limit the repair material's permeability based on this standard. During this test, crack-free specimens are formed in the laboratory or extracted in the field. According to ASTM C1202, the permeability of 400 coulombs is ''very good,'' while 4000 is ''very bad'' (Table 2).

Of course, the material's micropermeability has to be considered and limited – but only after macropermeability issues are successfully addressed by specifying an allowable drying shrinkage value. Specifications for cement-based materials with requirements for durability must set up criteria for drying shrinkage. The time to corrosion is first controlled by the transport of aggressive agents on the macrostructural level, and then on the microstructural level. Aggressive agents in the vicinity are ignoring diffusion and instead taking the path of least resistance – the network of cracks and microcracks.

The primary significance of deformations caused by moisture-related effects in cementitious materials is whether their interaction will lead to cracking. Here, the magnitude of the restrained shrinkage strain is the most important to be specified. Linking the two aspects of permeability (i.e. macro and micro) is a measure of the cement-based material as it is – its so-called protective character. There can be little doubt macropermeability is perhaps the most important of all.

The most critical engineering issues to be addressed to achieve durability are collectively called ''compatibility factors.'' The meaning of compatibility [1] in concrete repair composite systems relates to a balance of the physical, chemical, and electrochemical properties and deformations between the system components (e.g. existing substrate, repair, and transition zone between them). This balance ensures that the whole system can withstand stresses induced by restrained volume changes, chemical, and electrochemical effects without premature deterioration/distress over a designed period [2]. Figure 2 summarizes the factors to be considered in the repair material compatibility analysis.

Corrosion inhibitors. Many specifications call for use of corrosion inhibitors in concrete repairs. While these admixtures appear to offer added protection against corrosion in newly constructed concrete structures, there are some concerns and uncertainties related to their use in repairs. In other words, they can become an aspect of the problem, rather than a solution. When a corrosion inhibitor is added to the repair material, the local nature of the repair

Table 2. Evaluation of chloride ion penetrability based upon ASTM C1202 test results

Tabela 2. Ocena zdolności do penetracji jonów chlorkowych na podstawie wyników testu ASTM C1202

Charge passed (coulombs)	Chloride ion penetrability
> 4,000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very Low
< 100	Negligible

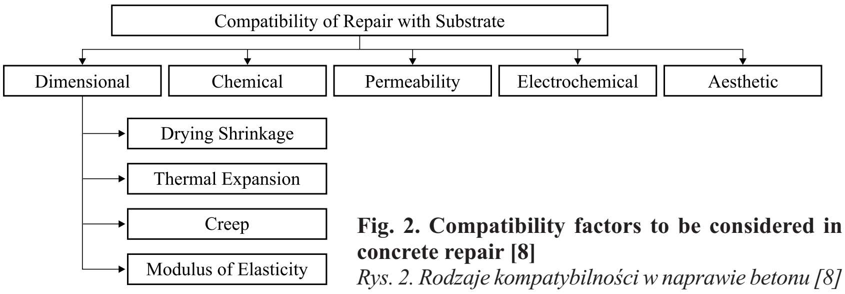

Fig. 2. Compatibility factors to be considered in concrete repair [8]
Rys. 2. Rodzaje kompatybilności w naprawie betonu [8]

does not address the whole structure's predicament if chlorides or carbonation are widespread. Even when the local repair contains the necessary concentration of the inhibitor, it can become a clean (i.e. non-corroding) cathodic area that stimulates increased corrosion around it, causing a "ring effect." Repair procedures of this type have in a number of cases resulted in early cracking and spalling in the original concrete adjacent to the repair.

Another concern is how to maintain the inhibitor's necessary concentration in the repair area. It is likely the inhibitor will spread beyond this point and migrate with water and other ions, causing the effective concentration to be reduced. The inhibitor solution can in fact move in response to concentration, moisture and/or temperature gradients occurring between different parts of the structure. Both moisture and temperature gradients determine the transport of water and other agents, via water, in the repair system. This flow can be significant when the structure is subjected to wetting and drying. It is also more than likely chloride ions from chloride-contaminated existing concrete will move into the repair phase by the aforementioned transport mechanism (Fig. 3).

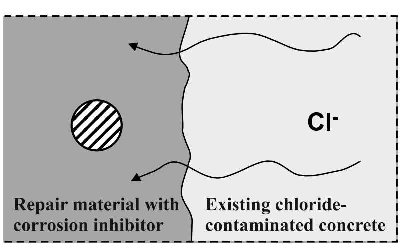

Fig. 3. Penetration of chloride ions from contaminated substrate into repair with added corrosion inhibitor
Rys. 3. Penetracja jonów chlorkowych z podłoża betonowego w środek naprawczy zawierający inhibitory korozji

Prescriptive or performance?

Specifications can be either prescriptive – or performance-based – there are many discussions underway regarding which better serves the intended purpose. Theoretically, the performance concept is ideal. However, considering the status of the concrete repair industry, it can be unsuitable because of the inadequate knowledge of those involved and the lack of evaluative techniques for some aspects of performance, especially in terms of durability. Simply put, performance can be specified by way of satisfying a particular test. Some attempts to develop performance tests in the concrete repair field are now underway, but their practical reliability has yet to be determined and application implemented.

With respect to the performance of repair materials, the situation is somewhat improved in that at least certain characteristics can be ensured. Nevertheless, many other behavioural repair characteristics, such as electrochemical activities, are largely unknown and difficult to predict. Caution needs to be exercised in establishing performance requirements, especially for repairing corrosion-related damage on structures subject to chlorides and marine environments [4, 5]. The performance approach may be applicable where the potential future performance is understood. However, this remains a challenge for repaired structures, as there is no proven link between lab-based performance test methods and actual in-situ performance.

Each issue, step, and requirement must be specified and controlled as performed. The actual myth of performance specifications for concrete repair projects might have risen from the assumption the contractor knows more about the achievement of durability than the engineer. Detailed guide specifications are needed in which the engineer, contractor, and inspector are given guidance in not only the "how" but also the "why." This allows for a real analysis of the situation and ultimately, a suitable decision to be made on how to proceed. The contractor should also be given direction concerning materials, methods, and equipment to be employed, unless he or she can demonstrate equal or better results by other means.

Conclusion

The engineering community involved in the design and implementation of concrete repair projects must recognize and accept the fact that the specification documentation is not a formality, but rather a critically important engineering guideline to fulfil durability requirements. Specification writing is a complex task requiring extensive knowledge of science, engineering, and in-situ practice. It also entails a considerable standard of responsibility on the part of the professional working with it.

Engineers have become accustomed to accepting heavy responsibilities. According to the Babylonians' ancient *Code of Hammurabi*, if a builder made a house and the house collapsed and caused the death of its owner, the builder was put to death. While the authors would not propose quite so harsh a measure for premature failure of a repair, they would nonetheless assert the industry must accept the responsibility for its shortcomings and strive forward to improve concrete repair projects.

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