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Holistic system approach to design and implementation of concrete repair

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Abstract

Concrete repair is a complex process, presenting unique challenges that differ from those associated with new concrete construction. The repair process must successfully integrate new materials with old materials, forming a composite system capable of enduring exposure to service loads, exterior and interior (inside the structure) environments and time. The durability of this composite system must be ensured on a systematic basis of daily practice – from the research, condition evaluation, realistic design objectives, detailed design and material selection, through construction practices and quality control. The paper discusses the key characteristics of a holistic system approach to concrete repair projects.

Keywords: Compatibility; Composite; Dimensional; Electrochemical; Holistic; Permeability

1. Introduction

Concrete repair is not a "band-aid" to a structure in trouble; it is a complex engineering task. And this task can be successfully resolved by applying system/holistic approach in design and implementation of repair projects.

One can speculate about future prospects of the repair industry based on an understanding of current trends, analyzing both opportunities and problems. A creative response to the infrastructure problem would ideally take the form of improvements in the approach to the repair activities which would be achieved through advances in technology resulting in more durable, more reliable and less expensive repairs.

In recent years the durability problems, poor performance, and most of all concrete repair failures have affected the image of concrete. The repair failures and endless "repair of repairs" made a substantial contribution to the current perceptions of concrete. The poor performance of many concrete structures is causing disruption and expenditure on remedial works which owners and society cannot afford and do not wish to see repeated. Too often concrete repair is perceived as the problem, rather than the solution. Current state of affairs in the industry will not allow us to achieve the major improvement in as-built durability required for concrete structures.

The majority of concrete repair problems, including the condition evaluation of existing structures, engineering objectives, design, material selection and construction are of such magnitude and complexity as to require the most systematic and rational approach possible. This paper summarizes the key characteristics of an integrated system approach to concrete repair projects. The "system concept" or approach to addressing concrete-repair tasks is a key to real solutions to real problems.

The field of concrete repair, like life itself, is competitive; forcing us to continually progress and change. This paper is a provocation to foster such progress. Progress is in reality a conception embodying the most profound and the most potent ideas at work. Concrete repair is a complex process, presenting unique challenges that differ from those associated with new concrete construction. The repair process

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must successfully integrate new materials with old materials, forming a composite system capable of enduring exposure to service loads, environment and time. The durability of this composite system must be ensured on a systematic basis of daily practice, from the research, condition evaluation, design objectives, detailed design and material selection, through construction practices and quality control. Every means of rendering concrete repair technology more reliable has an enormous engineering and economic significance, considering the present day volume of deteriorated/distressed concrete structures.

2. Holistic system approach

The term holistic refers to an understanding of a phenomenon or structure in terms of an integrated whole, whose properties cannot be deduced from the sum of the properties of the constituent parts. To deal with complex systems in accordance with the holistic approach, we must integrate experimental knowledge with available scientific knowledge. Of course, when addressing a complex problem, the whole system can be decomposed and organized into hierarchical subsystems. But those subsystems are not independent; they must be integrated into a whole. Instead, in our studies of a complex repair system, too often we treat the data on a component – reductionist basis, instead of the holistic approach. This is what is wrong with science, engineering and practice in the concrete repair field. Following is a brief review of these two approaches and their differences.

Reductionism consists of the belief that everything can be reduced, decomposed, or disassembled to simple parts, phases, conditions, and substances. Analysis consists first of taking apart what is to be explained; disassembling it, if possible, down to the independent and indivisible parts of which it is composed; second, of explaining the behavior of these parts; and finally, of aggregating these partial explanations into the explanation of a whole. For example, the analysis of a repair problem consists of breaking it down into a set of as simple problems as possible, such as damaged area, repair material and method of application, longevity of the repair in the affected area, etc. Solving each, and assembling their solutions into a solution as a whole. If the engineer succeeds in decomposing a problem into simpler problems that are independent of each other, aggregating the partial solutions is not required, because the solution to the whole is the sum of the solutions to its independent parts. Therefore, the effect of the repair on the whole structure, and the durability of the repaired structure is ignored.

The year 1940 can be cited as the beginning of the end of the Reductionism Age and the beginning of the System Age. In the new age the reductionism thought is being supplemented by the concept of expansionism, system concept and the synthetic mode of thought; it turns attention from ultimate elements, to a whole with interrelated parts, to systems.

In the reductionist mode, an explanation of the whole was derived from explanations of its parts. In synthetic thinking, something to be explained is viewed as part of a larger system and is explained in terms of its role in that larger system. The system concept is more interested in putting things together than in taking them apart. The synthetic mode of thought, when applied to system problems, is called the systems approach.

A holistic approach to repair ensures that no part of the system is overlooked and takes into account the concurrent interaction of many factors and the consequent physicochemical and electrochemical changes occurring in the composite. A shift in the science of concrete repair durability from a reductionist to holistic approach is also necessary before we can develop test methods, specifications and codes that are truly applicable to the durability of repaired structures. Absence of the holistic system concept in designing and implementing concrete repairs clearly demonstrates the fallacy in the current repair field. Components of the system, subsystems are very important, but only to the end that the purpose of the whole system is achieved through functional relationships linking them. For example, when repair to the bridge prematurely fails and no longer serves its purpose, it will be called "junk", regardless of what caused the failure – design, materials, workmanship, or a combination of these. The entire system failed. For the concrete repair industry, – including design engineer/architect, owner, material manufacturer, and contractor, – in order to successfully meet the needs of the future, the entire process of "concrete repair" should be considered and the system concept shall be adopted.

Systems design can be defined as a process of selecting, putting together, and/or developing the components (materials and procedures) that will produce a system that will optimally satisfy the goals. Optimality, in this sense, indicates a system, a repaired concrete structure that achieves its finest level of designed performance.

Holistic system approach, – the fundamental requirement of the design process, – includes such critical elements as the establishment of the causes necessitating the repair/rehabilitation of the structure, objectives and criteria, synthesis, analysis, construction, testing and acceptance. Engineering judgment must be applied, and previously learned technical expertise must be synthesized, recalled, and put together to solve the problem at hand. The effective use of the holistic system approach will help ensure that the repair projects address the true problems at hand. Projects that do not do this may not, if implemented, produce useful, long-lasting repaired structures to meet the desired needs.

3. Concrete repair – a composite system

The repaired concrete structure is a composite system of composite materials exposed to the interior and exterior environments and their interaction. The system is represented structurally by three basic phases or subsystems:

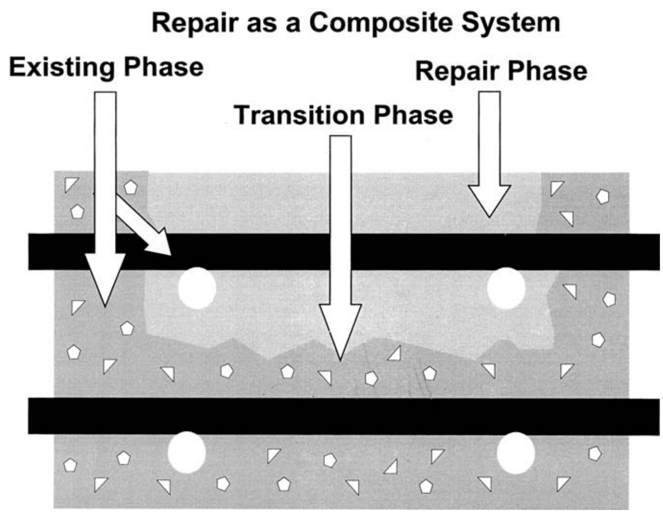

Fig. 1. Composite system of concrete repair.

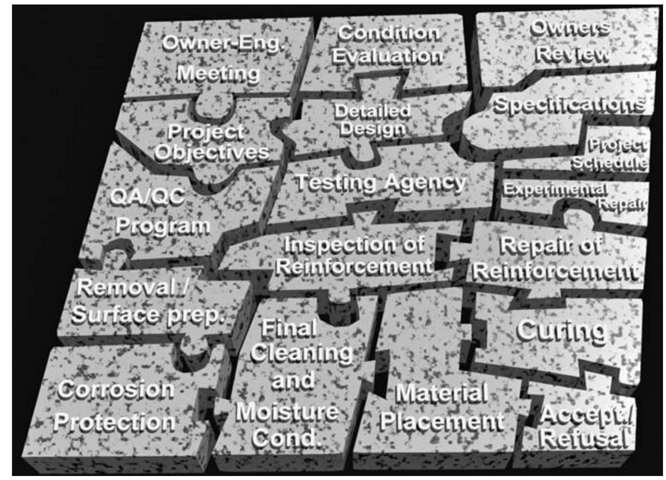

Fig. 2. Concrete repair system.

the existing substrate, the repair material, and the transition zone between them (Fig. 1).

The entire process of implementation of a concrete repair project is also a system encompassing the following important subsystems:

- Assessment of the condition of existing structure (degree of deterioration/distress).
- Assessment of cause(s) of deterioration/distress.
- Establishing the nature and severity of the interior environment in the existing structure.
- Ascertaining the probable service life of the repaired structure.
- Establishing realistic design objectives.
- Selecting an appropriate repair system.
- Developing repair details and specifications.
- Implementation of the repairs as specified.

Concrete repair project is also a system on an organization level, and includes such subsystems/participants as:

- Owners.
- Multidiscipline engineers.
- Material manufacturer.
- Contractor.
- Testing agencies.
- Quality control.

A system or "organized complexity" may be circumscribed by the existence of "strong interactions". Unfortunately, the prevailing way we approach the repair/rehabilitation projects presently may be described by two extremes: unorganized complexity or organized simplification. In both cases, the unfortunate results are well known.

The system approach, the effective interaction of all elements or subsystems in a repair project is somewhat similar to a jigsaw puzzle (Fig. 2). To put the puzzle together successfully, it must be workable. All parts must be present, and of the proper geometrical shapes, to fit the adjoining pieces. If some pieces are missing, or if the geometry does not fit the adjoining pieces, the puzzle is not solved. Similarly, if not enough attention is paid to each element composing the concrete repair system, our task is not solved, and the project will be a failure. Critical factors to be considered and adequately addressed in repair projects are presented in Fig. 3.

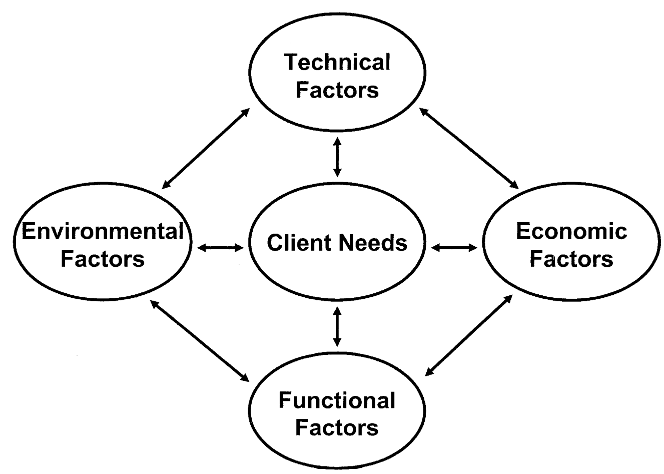

Fig. 3. Critical factors to be addressed in a repair project.

4. Compatibility in repair systems

To understand how various factors affect the performance of a composite repair system we have to define, once again, the term 'compatibility'. The meaning of compatibility in concrete repair systems relates to a balance of physical, chemical and electrochemical properties and deformations between the repair and substrate that ensures the system as a whole withstands stresses induced by restrained volume changes, chemical and electrochemical

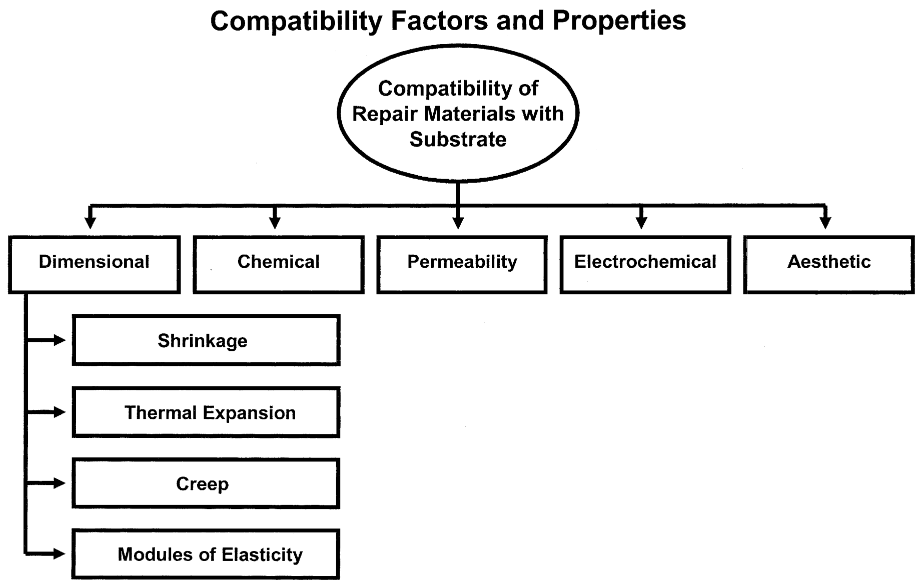

Fig. 4. Compatibility factors.

effects without premature deterioration/distress over a designed period of time [1]. Fig. 4 presents the factors to be considered in compatibility analysis. Several of these factors are discussed in this paper.

Dimensional compatibility. One of the most important compatibility components is dimensional compatibility of repair materials with the existing substrate, which includes the following factors:

- Drying shrinkage of the repair material.
- Thermal expansion or contraction differences between repair and substrate materials.
- Differences in modulus of elasticity causing unequal load sharing and strains resulting in interface stresses.
- Creep properties.
- Relative fatigue performance may result in initial tensile stresses that either crack the repair material or cause debonding at the repair–substrate interface.

In the course of the discussion concerning compatibility, it is necessary to mention that the proclamation that only repairing "like with like" can offer a durable solution, and that the repair material to be compatible with existing concrete should have "composition and properties similar to the substrate concrete" is a fallacy, which lacks technical basis. Many repairs to concrete structures are necessitated by inadequate quality of concrete leading to extensive shrinkage cracking, alkali–silica reaction, sulfate attack, etc. To follow the above recommendations we have to use similar "junk" as a repair material. Now, let us assume that the concrete in existing structure to be repaired is of adequate quality. Then, theoretically, it is a good idea to repair "like with like". But is it practically possible?

The composite repair system is formed as a result of setting and hardening of a semi-liquid substance (the repair material), placed on the surface of a substance in solid state (existing concrete). So, in such conditions the only "like with like" will be a repair with a prefabricated concrete element. But even in this case, "like with like" is impossible, because the existing substrate has "unlike" chemistry and electrochemistry. The concrete substrates are different one from the other in age, quality and surface exposure; from the relatively new concrete to the 80 year old ones exposed to various temperatures, relative humidity, chemical aggressive environment and mechanical loads. To make the argument even more convincing for the "like with like" proponents, following is a definition of compatibility by the Webster Dictionary: "The capacity of two or more entities to combine or remain together without undesirable after effects: mutual tolerance."

The lack of understanding of the nature of the system in general, and "dimensional compatibility", in particular, is frequently the source of many failures in practice.

Permeability compatibility. Permeability compatibility is another critical issue. The majority of repair publications strongly recommend using as low as possible permeability materials in repair systems.

Currently, permeability of a small material sample is measured according to ASTM C 1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration". This test is applicable for laboratory use only; in real life structures it measures permeability between cracks only (Fig. 5). A few cracks in the repair will drastically offset the benefit of having a low permeability repair material. Cracks and microcracks originating from the repair surface play a much greater role in reducing the impermeability and longevity than the permeability of the repair material itself.

Permeability of repair materials is one of the primary properties of importance, and more work is needed on

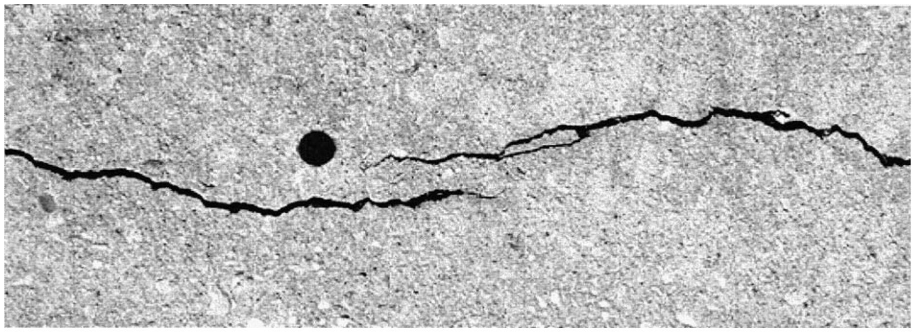

Fig. 5. Specimen shows low permeability concrete. Is it?

defining what degree of permeability of repair materials shall be recommended for different repair situations. Most likely, there is no single recommendation as to whether very low, or compatible permeability materials with existing concrete, are more effective. It depends, in the author's view, on particular transport mechanisms in the repair system. Transport of substances through and in the repair system is a very complex process, consisting of a combination of liquid flow through macro- and microcrack systems, capillary transport, diffusion and osmotic effects. The exact contribution of each process needs to be quantified in each particular situation. The effects of such variables as location of the repair in the structure, chemical environment in the composite repair system, amount and distribution of cracks in both phases, temperature, moisture and stresses need to be considered.

Electrochemical compatibility. The precise analysis of electrochemical compatibility in repair systems is very difficult, if not impossible. The interior environment in the system is constantly changing, and electrochemistry is also constantly changing as a result of interaction with exterior and interior environments, with innumerable physical and chemical changes in the system.

The superposition of a repair material layer over chloride-contaminated concrete could seal in a source of continuing corrosion. The probability of such corrosion to occur is significant. Therefore, a successful repair, lasting 15–20 years, is a very seldom-occurring phenomenon; it is more a myth than a reality. The application of various corrosion protective techniques and materials is largely empirical. Further developments using a more rational approach are hampered by a lack of understanding of electrochemical compatibility (or incompatibility) in the repair system. In published literature, there is practically no information on the subject. The concern of the concrete repair industry regarding the electrochemical compatibility (or incompatibility) occurring over time in a repaired structure may be alleviated if more definitive information on the subject was available.

The synergetic effects of several critical diverse environments present along the electrically continuous rebar, in addition to differentials in stress states, significantly add to the complexity of the problem. The influence of the repair phase on the existing phase, change in chemical composition, distribution of aggressive agents, oxygen, moisture, admixtures and other factors on the electrochemical properties of the repaired system all need much more attention and research. This research must be more practical, more field oriented.

5. Design of a repair project

The ideal concrete repair project would start with the comprehensive condition evaluation of the existing structure, establishment together with the owner the realistic project objectives, definition of the performance criteria related to the existing and expected interior (inside repaired structure) environmental conditions.

The condition evaluation prior to establishing the project objectives is of critical importance. If inadequately performed, there is no chance for a successful project. Unfortunately, this phase of the repair project often becomes a low-budget formality, underestimated by the structure's owner, and sometimes by the engineer.

The first step toward improvement is to educate the owners of structures to better understand the basic decisions which govern the service life of their concrete structure. To make them see both the short-term and long-term technical and economic consequences of alternative decisions. To perform this task is the obligation of the engineer. But, in order to perform this task effectively, the engineer has to be knowledgeable, well informed and honest. If we make a painstaking survey of current repair engineering practice, we are forced to admit that often it lags away all three of the above qualities.

Just take a look at some of the condition evaluation reports. There is delamination, spalling, cracking and steel corrosion with substantial section loss. You conclude that the "client is dead or almost dead". Then "band-aid" repairs are recommended, and all of a sudden 20–30 years of "maintenance-free" service life is promised. Operation successful – "the dead is alive and well".

But even in adequate quality repair projects we are making enormous approximations related to the interior environment in existing structures, rather than perform our analysis, solutions and performance predictions based on the in-depth condition evaluation. In North America, and we suspect elsewhere, this has contributed to poor repair performance.

The knowledge, experience and integrity of the engineering team are indispensable. The condition evaluation phase of the repair project is of paramount importance, and these will ensure that with adequate design, repair materials and workmanship, the intended service life of the repaired structure will be obtained with a sufficiently high probability.

The biggest failure, though not visible, is often self-imposed by the engineer, by setting unrealistic project objectives. It is, on one hand, the matter complicated by commercial considerations and the peculiarities of engineer psychology – and, on another, the desirability of "getting the job" – in which also the matter of dollars and cents is so large a factor. Lack of knowledge, in many instances, is also a contributing factor. Ethical factors often contribute to the attitudes adopted. If the design engineer acts responsibly, with a keen realization of the existing conditions and future performances, the project objectives will contribute to success, and not to the failure.

The majority of the repair projects around the world are associated with damage caused by corrosion of embedded reinforcing steel. Repair projects are initiated when the corrosion process is long past the initiation phase, usually at the well advanced stages of the propagation phase. Understanding this fact is critically important in setting the design objectives, and it also highlights the issues that are important for future repair performance.

Unless the repair project provides for "global" cathodic protection, the risk of corrosion will always be there. The reinforcement in a repaired structure will be under attack internally and externally. The agents of corrosion are always present in the interior and exterior environments, and it is up to us to decide on the extent and quality of our defense. What we require is for the defeat not to occur before the design objective has been reached. To ensure the best future performance of repaired concrete structure, the events which threaten their durability presently, and which may threaten in the future, must be identified. But this is an extremely complex task, related to electrochemical compatibility in repair systems.

The design of durable repaired structures with realistic performance objectives will then have to be concentrated on two parallel activities.

- Ensuring adequate resistance to the predicted internal (inside the repaired structure) and external environmental effects.
- Providing adequate structural capacity and safety under the expected loading.

The repair project objective is very seldom related to prevention of further deterioration. The realistic objective is to ensure sufficiently slow deterioration, to prolong time to the next remedial action, for as long as practically possible.

Now, the question is how can one adequately predict the future service life of the repair, or the time to the next remedial action? How to predict the time to reach a certain level of deterioration by separating the various rate determining phenomena underlying the corrosion of reinforcing steel? Nothing is uniform in a repaired system; it is a "uniform nonuniformity" in everything. Some see the answer in prediction models. Such models, no doubt, are useful not only as intellectual exercises but also for the knowledge of the structure and its behavior, which would not be learned otherwise. But the models cannot and should not be used for predicting the service life of repaired structure.

The prediction of the service life, the repair objectives, should be based on rational engineering analysis, knowledge from observations and through "trial and error", with both good and bad experiences. As Bronowski said a "Good prediction is one which defines its area of uncertainty; a bad prediction ignores it" [2].

The detailed design and specifications must contribute to the solution and not be the major problem. Constructability issues must become an integral part of the project. Geometry, access, amount and spacing of reinforcement, climatic conditions, available equipment, local engineering and labor skills, quality control, and economical considerations have to be analyzed. The designer needs more knowledge about service life characteristics or repair systems, more knowledge about the repaired structure interface with its environment and definitely more knowledge on the present and future changes in the interior composite repair system environment. There is a sea of papers which address the durability of concrete that is affected by external parameters. The aggressive factors of internal origin are ignored simply because the subject is too complicated. When the exterior environmental conditions to which a repaired concrete structure would be exposed to during its remaining service are well defined, and interior environmental conditions in the repair system are properly analyzed it is the responsibility of the Engineer to tailor the design of the repair methods and materials.

6. Repair materials

Unquestionable progress has been made in the field of repair materials. The menu of materials for particular applications is extensive, but the material that has the required properties for a particular application is only one step in the complex system that makes up the totality of concrete repair.

There is a lot of lip service lately, paid to so-called "high-performance concrete" and like materials. If someone were to analyze the construction industry's fashionable catchwords (catch terms), he would find "high-performance" materials high on the list. King Solomon, in his wisdom, found it rather easy to determine who the child's mother was. Fortunately, he was very lucky that, in his time, it was not necessary to decide who the father of "high-performance" concrete was. The term pervaded the construction field and penetrated into marketing, technology, science and mass media. It became an exotic topic at conferences, symposiums, and scientific colloquiums; it put aside technological problems and demands of the number one construction material in the world-conventional concrete. Producing papers on high-performance concrete has become a growth industry.

It may be appropriate, therefore, to discuss the topic of "high-performance" concrete, what is means (if anything); is it a step forward in concrete technology or an exercise in terminology, real activity or simulation of activity? Lately, some are explaining that "high-performance" is synonymous with "high-strength", but high compressive strength is not an indication of durability and performance. Quite on the contrary, often it has a negative effect on durability. The reality is that the 21 MPa (3000 psi) "low performance concrete" is more crack resistant, and most likely, will help to achieve better durability in many applications then the 55 MPa (8000 psi) "high-performance" material.

Thomas Jefferson wrote to Dr. Benjamin Rush in 1800: "When great evil happens, I am in the habit of looking out for what good may arise from them as consolation to us; and Providence has, in fact, so established the order of things as that most evils are the means of producing some good".

As we have accelerated the pace of concrete construction, we have required cement-based materials to become stronger sooner and to set faster. At the same time, we increased concrete's brittleness and reduced its resistance to cracking. We have damaged concrete's "immune system". Concrete that continues to hydrate offers increased resistance to aggressive agents. The "old-time" concrete used to gain strength, density, and the ability to resist environmental attack over its service life; "new" concrete does not, because it already reached its potential in one week or sooner.

The worst sin in an engineering material is not lack of strength or stiffness, but lack of resistance to initiation and propagation of cracks. One can allow for lack of strength or stiffness in design, but it is much more difficult to allow for cracks which are life-threatening wounds on concrete bodies. Our "achievements" in high-strength/"high-performance" materials created an epidemic outbreak of cracking. If anything, what all of this tells us is that, while not blind, we see without being able to perceive the differences between illusion and reality.

Because repair failures may lead one to believe that the material did not perform well, the repair solution if often focused on "better materials". But what is a better material? Experience clearly demonstrates that conditions that impair the effectiveness of a repair material in one structure would not necessarily impair the effectiveness of that same material in another structure. Material selection factors are shown in Fig. 6.

We still need, and will work on, improvements in cementitious repair materials.

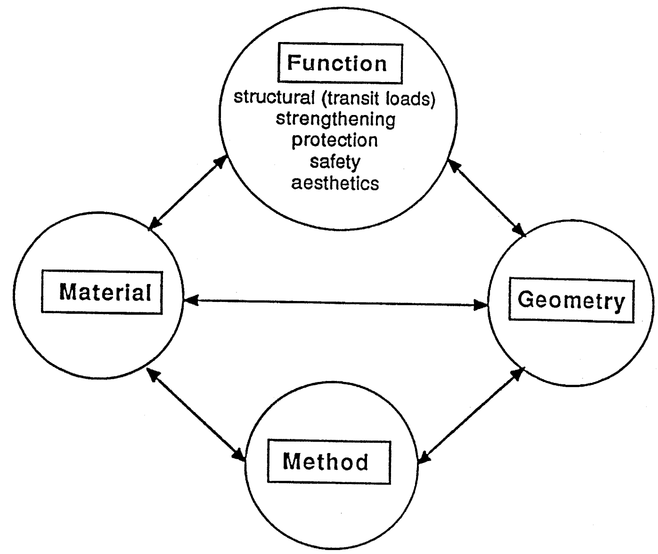

Fig. 6. Material selection process.

Nonetheless, there are limits to what we can achieve in materials science. Some of the limits are dictated by physical laws. For example, the elasticity, stiffness and tensile strength of material depend on the strength of its atomic bonds. Thus, there are inherent physical limits to the tensile strength and deformability of cementitious materials, and materials science cannot alter that fact.

7. Science

Science in concrete and concrete repair technology are critical elements of the entire concrete repair system, and urgently need improvements. The needs of research, at least for far-reaching one, are often established by the mental processes going on in the minds of research workers, rather than by the demands of the industry. It is hard to disagree with Calleja [3] who indicated that "in the field of durability as well as in many other fields of cement and concrete research, most of the research work runs around the same themes, using the same methods, applying the same ideas, and arriving repeatedly, almost always, at the same partial and non-decisive conclusions".

The research worker often fails to pursue his research achievements all the way to its practical application. We need more young individuals to be well educated and to get involved in concrete repair research and engineering. Very few young engineers are an important part of applied research in the concrete repair field. Young age is not an excuse, you do not have to be gray and/or bold to make a valuable contribution; maybe on the contrary. Isaac Newton formulated the Law of Universal Gravity at the age of 23; Albert Einstein created his theory of Relativity at the age of 26.

The concrete science, in general, made a significant progress in the last 50 years. But even then, the sound judgment of the engineer is always required because there is Science, and there is Common Sense. Both must learn to assimilate into their methods and basic ideas the underlying uncertainties and gaps in existing knowledge. As Bronowski stated [2], "Science is a very human form of knowledge. We are always at the brink of the unknown. We feel forward for what is hoped. Every judgment in science stands on the edge of error, and is personal. Science is a tribute to what we know, although we are fallible".

8. Conclusions

1. The progress in concrete repair field has been slow, pedestrian, but always forward. And, if we are in agreement that the future is controlled by the amount of work yet undone, then the future of the concrete repair field is assured.
2. System concept, in design and implementation concrete repair projects with the required durability, under conditions defined in advance has become a task of first magnitude. Adapting and implementing the system concept will undoubtedly lead to a transformation from "chaos to order". Every means of rendering concrete repair technology more effective has an enormous economic and engineering significance, considering the present-day volume of concrete structures in need of repair.
3. It is our goal to produce "high-performance" concrete repairs; repairs that successfully perform the intended purpose for the designed service life. However, our goal will remain just a dream until we can achieve high-performance in: research and education, condition evaluation, design, material manufacture, training and supervision, in situ workmanship, and quality control.

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