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THE CHALLENGE OF NUMERICAL MODELING OF STRAINS AND STRESSES IN CONCRETE REPAIRS

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ABSTRACT

Designers presently have no quantitative rules to evaluate which of several proposed repair designs is the most appropriate in a given situation. A numerical model that would allow us to compare, on a quantitative basis and with relatively little work, different repair scenarios would be very helpful. This paper describes the problems that need to be solved in order to develop a realistic numerical model of the mechanical behavior of thin concrete repairs. The "*critical thickness*" concept is defined as the superficial zone where there are steep relative humidity and temperature gradients due to daily and seasonal weather changes. Cracking of the repair layer is maximum within this "*critical thickness*" because this zone is subjected to significant strain cycles. *© 1997 Elsevier Science Ltd*

Introduction

Countless concrete structures have been built since the last world war. Many of these are now deteriorated and need to be repaired. Achieving durable repairs is of primary importance because the costs involved are generally very high. For the owner, repairs that fail after only a few years represent an economical nightmare, since construction expenses are capitalized on a long term basis. Experience shows, however, that the design of durable concrete repairs can be as complex as the design of new structures because each damaged structure imposes its own set of conditions (1).

In this paper, a concrete repair is defined as a thin concrete layer (≈50-150 mm) cast on an existing structure to replace that part close to the surface which is deteriorated. A durable repair can be defined as a layer of new concrete that will bond firmly to the old concrete for the total length of the expected service life of the repair and will not develop cracks that will reduce the expected level of protection. The use of durable repair materials does not per se insure the durability of the repair, since the repair durability is also related to the *"compatibility"* between the new repair material and the existing structure (1-8).

The concept of "compatibility" covers a broad range of properties, from the chemical compatibility to the elasticity modulus compatibility and the other volumetric change compatibilities. The basic idea is simple: if the repair material and the repaired concrete are too different, they will not "work" together and rapid deterioration will most likely occur. However, since the old concrete is mature and the repair concrete properties are rapidly evolving, "compatibility" between the new and the old concrete only occurs at a given moment, and this moment is not the same for each property. Each moderate mismatch adds to the overall larger mismatch that will induce cracking if the "compatibility" is insufficient. Cracking of repairs should be avoided because it compromises not only the durability of the repair but also the protection of the rebars. The basic problem is that no quantitative design rules exist which would allow us to determine if the compatibility is "good", "poor" or "insufficient" in order to rank different repair options.

Designers presently have no quantitative rules to evaluate which of several proposed repair designs is the most appropriate in a given situation. What can be found in the literature are various comparative criteria that apply to each property of the repair material and of the substrate (6, 9-11) one at a time. What is missing is a sound method to analyze the properties of various repair solutions to determine which solution is preferable. A number of interesting approaches have been proposed by Plum (9) (a repair function), Marosszeky (12) (an em-

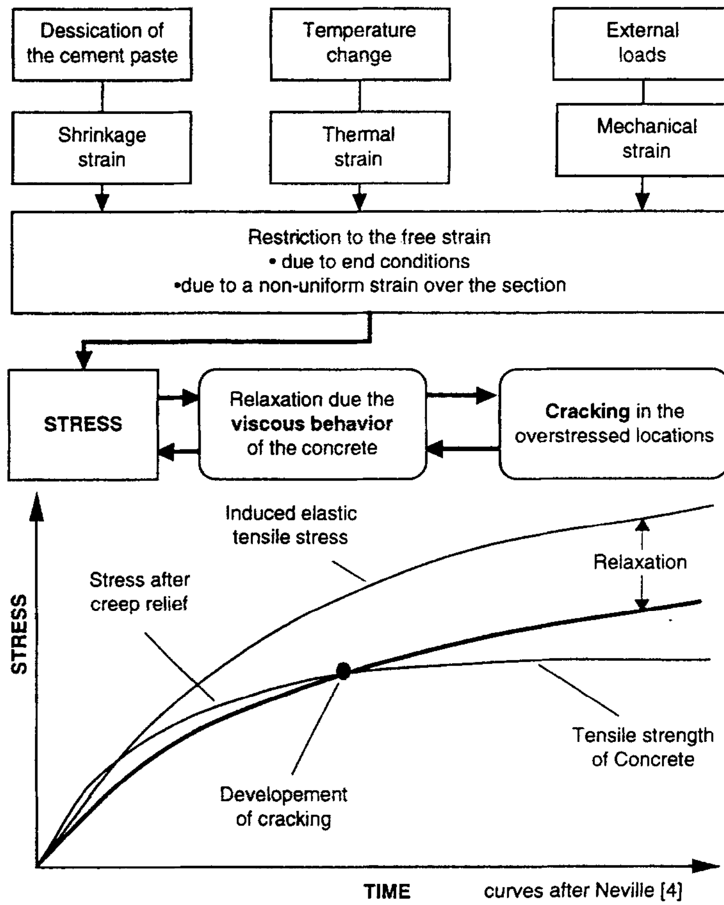

FIG. 1.
Schematical illustration of the stress build-up in repairs.

pirical "Stress Performance Margin") and Yuan & Marosszeky (13) (a numerical model), but a lot of work remains to be done before the assessment of the potential service-life of a repair can be determined from laboratory tests.

Practical experience as described in the technical literature indicates that an adequate durability of the bonding between the new and the old concrete can be obtained with appropriate care (3, 14-17). However, no repair will be durable unless the repaired layer is free of severe cracking (12) due to tensile stress. These stresses build up as the sum of the hygrally, thermally and mechanically induced strains increases (see Figure 1). The shrinkage and thermal strains are restrained by the bond with the old structure, but the stresses induced are partly relaxed by "tensile creep". Cracking will occur if, at a given moment, the overall balance between strains, creep and tensile strength is exceeded. This concept has been illustrated clearly by Neville (18) but, unfortunately, the creep curve shown in Figure 1 cannot be obtained from any simple test method because the shrinkage induced stresses are continuously increasing with time, which does not occur in a laboratory test where a constant sustained load is applied. Moreover, observing that cracking can happen is not as important as estimating the crack width, depth and location (19). Shallow surface cracking will not have the same detrimental effect as cracking down to the rebars or debonding at the interface between the new and old concrete.

The study of the cracking behavior of repairs due to restrained shrinkage can be performed using laboratory tests with specimens cast in a rigid frame (20, 21). However, a very precise and delicate setup is needed, and only the average stress over the section can be evaluated. The observation of full scale repaired elements (slabs, beams, columns, etc.), either in the laboratory (22) or on real structures (14), is useful, but this is an expensive approach that outputs only limited data considering the numerous possible repair and exposure conditions.

The preceding considerations are incentives to develop a numerical model of the stresses, strains and resulting cracking of repairs due to restrained shrinkage and thermal effetcs. Theoretically, an operational model is the most cost effective way to compare several design alternatives on an objective basis. However, there are still obstacles to overcome before such a model can be developed. The literature on the modeling of the long term behavior of concrete confirms the complexity of the problem (23-30), and complete and precise models for practical applications are still rare (31). This paper presents a general pattern of analysis and explains the challenges to overcome in order to obtain a realistic numerical model of the mechanical behavior of thin concrete repairs. The simulation of the overall behavior of repairs, including items such as chloride ingress through cracks and the development of corrosion, is considered as a goal which will likely take several years to reach.

Basis for a Model of Concrete Repairs

Importance of Coupled Phenomena. Portland Cement concrete is a very complex material and most of its properties are coupled to some of the others in various ways. For instance, a variation of the temperature of the concrete not only induces a thermal strain, but also modifies the hygral equilibrium, the elastic modulus and the creep behavior. However, for the sake of simplicity, an efficient numerical model will not consider every possible coupling but only those that are fundamental to avoid large deviations from real behavior. In repairs, strains and stresses begin to be induced in the first days, during which cement paste matures rapidly. The evolution of the properties over time can not therefore be ignored in the development of a model. This evolution of course seriously complicates the numerical analysis.

Thermally Induced Strains. Weather exposed structures respond to daily and seasonal temperature changes. The strains that are induced can be calculated according to the laws of heat exchange and of thermal expansion or contraction. These strains occur simultaneously with the hygrally induced strains and should be considered in a stress analysis. However, thermal strains are easier to calculate than hygrally induced strains and little attention will be paid to this phenomenon in the following discussion.

Desiccation of the Cement Paste. In a typical thin repair, the source of the time-dependent stress development is the desiccation of the cement paste which is due both to the internal desiccation (cement hydration) and to the evaporation of the capillary water from the surface. In the former case, the induced shrinkage is uniform over the cross section of the element. On the opposite, drying from the surface results rapidly in a steep gradient of free water content (perpendicular to the surface), in part because the coefficient of vapor diffusion is not constant but is a function of the water content which varies over a wide range.

Most models of the loss of water by drying simply simulate continuous drying in uniform conditions (such as 23°C and 50% R.H.) (32-34). Water content or relative humidity (R.H.) is calculated as a function of time and position. According to calculations such as those shown in Figure 2, the R.H. at the center of a concrete specimen can decrease to 60% within two years. The reality of weather exposed structures is, however, much more complex, since temperature and humidity conditions are continuously changing on a daily and seasonal basis (sun, rain, wind, freezing, etc.) (35,36). These changes influence the very surface of the concrete but desiccation only a few centimeters below the surface is much smaller than what can be calculated for continuous drying conditions. For instance, the relative humidity inside highway concrete barriers located in Québec City (Canada) was monitored (barriers were 12 years old when monitoring began) (37). The R.H. was measured with a 30 cm probe inserted in such a way that the sensor was located about 10 cm from the surface. For eight series of

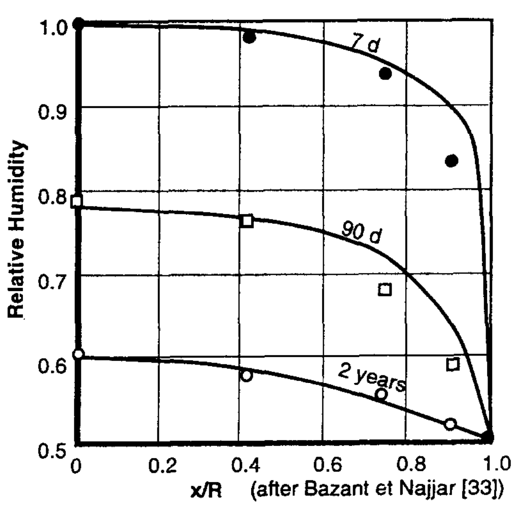

FIG. 2.

Calculated drying within a cylinder continuously exposed to a relative humidity of 50%.

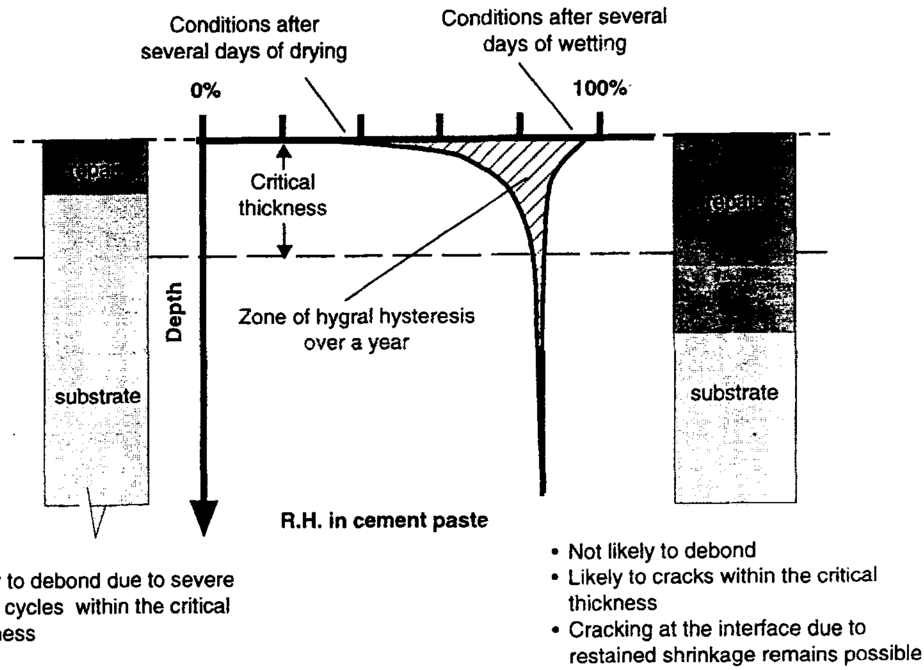

FIG. 3.
Illustration of the critical thickness concept.

measurements performed over 4 years, the values fluctuate around 90% in the reference barriers and 80% in those protected with a silane based vapor permeable sealer.

The Critical Thickness Concept. The surface of a concrete structure is obviously more affected by the weather conditions than its core. In the literature, the superficial layer (termed "covercrete", "skincrete", etc.) is often distinguished from the core (termed "heartcrete", "corecrete", etc), but the thickness of this superficial layer varies significantly, from as little as 1-5 mm to 25-50 mm, depending on the viewpoint (38-40). If a concrete repair is as thin as the "covercrete", the interface between the new and the old concrete will be located within the most severely exposed part. This suggests that there probably exists a "*critical thickness*" for a repair layer. Within this *critical thickness*, there is a steep gradient of relative humidity and temperature due to daily and seasonal weather changes (see Figure 3). This induces significant strain cycles that enhance the possibility of cracking. On the opposite, beyond the *critical thickness*, the hygral and thermal state varies only slowly and tends, for an outdoor structure exposed to the Eastern Canadian climate, to reach an average level of humidity much higher than the usual 50% or 60% utilized in laboratory tests. The stress magnitude and the cyclic variations at the interface are thus related to the position of the interface with regard to the "*critical thickness*".

Fortunately for the designer, the *critical thickness* is more than a concept. It is a quantity that can be calculated and used as an input data for the design of durable repairs. However, there is no such thing as a unique *critical thickness* because, on the same concrete structure, certain surfaces are exposed directly to sunshine and frequent rain, and others remain protected and never get wetted by rain. But, in all cases, there is only a limited layer that suffers a large number of hygral and thermal strain cycles. For research purposes, the determination of the *critical thickness* can be performed by modeling the hygral changes in a given section over a typical year, using precise material parameters and realistic weather exposure conditions (temperature and relative humidity). For design purposes, it will be possible to propose typical values when sufficient cases have been analyzed.

Modeling the hygral changes due to weather conditions is quite complex and can be performed using the laws of thermodynamics, considering the equilibrium between the three phases of water (vapor, liquid and ice). Such models have been used for a long time in building component research and could be extended to civil engineering concrete structures. Kumaran et al. have reviewed and discussed 27 such models actually available (27). Considering the present know-how, the level of precision to be expected is not a millimetric map of the relative humidity inside a given cross section but a realistic evaluation of the humidity displacements inside concrete under the driving forces of temperature and humidity variations in the surrounding air. The TCCC2D model developed by IRC's Building Performance Laboratory (41) is presently being used to investigate the critical thickness concept. The precision of the calculated humidity profiles could be verified by comparison either with a number of local values obtained from R.H. probes or with Gamma-Ray densimetry measurements made on concrete specimens exposed to known humidity conditions. These techniques do not allow precise measurements in the first 5 to 10 mm from the surface. Thus, the calculated values of R.H. in this zone cannot be directly verified, and the strains and stresses obtained from any model in the unprobed superficial zone will have to be considered with caution.

Shrinkage Strains. There appears to be a consensus among investigators that the shrinkage strain of a concrete specimen is directly related to the humidity level in the pore system, even if only empirical relations have been proposed up to now (30, 32, 36). A common assumption is that the level of stress does not influence the water diffusion mechanism, and no physical evidence has yet invalidated this assumption. Hence, the calculations concerning the desiccation of cement paste for the whole life of the structure can be made independently of the mechanical stress analysis. The shrinkage strains can thus, for instance, be calculated only in a second step of the global analysis in which, at each time step, the R.H. is considered as an imposed value at each point of the cross section of the specimen.

The particularity of repairs is their small scale. In a usual laboratory shrinkage test, the water content inside the specimen is not uniform and the measured strain is only a global value that characterizes the "cross section behavior" which can be influenced, in addition, by stress relief at the surface due to cracking. Considering the R.H. gradient in the repair layers which induces highly non-uniform stresses (that must be correctly assessed to determine if and where cracking will occur), the data from normal laboratory shrinkage tests can not therefore be used directly to modelize a repair layer. Moreover, the wall effect influences the paste/aggregate ratio in the first 5 to 10 mm from the surface and shrinkage is clearly higher in this zone. The shrinkage strain for a given R.H. is also related to the maturity of the cementitious matrix. Furthermore, the R.H.-strain relation is not completely reversible, but the strain hysteresis during cycles of shrinkage and swelling is not extensively documented. In fact, the whole relation between the humidity level in the pore system and the shrinkage strain needs to be investigated further. According to the *critical thickness* concept, the layer most affected by humidity cycles is small and special test methods will be necessary to examine the strain behavior in this zone.

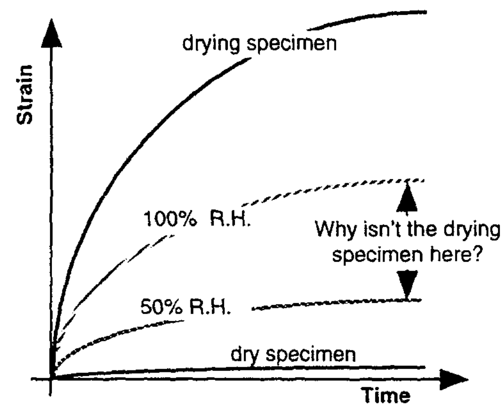

FIG. 4.
Illustration of the Pickett's paradox (creep strain vs. time).

Stress Relaxation by Viscous Behavior. For normal reinforced concrete structural design, the knowledge of creep and relaxation in tension is useless because the tensile contribution of concrete is neglected. In the case of repairs, restrained shrinkage builds up tensile stresses in repaired areas and a proper evaluation of the relaxation behavior is essential to determine with a sufficient degree of probability if cracking will occur. Modeling repairs without taking creep and relaxation into account has been presented, but the authors have recognized that the results obtained can not be considered realistic (4, 5). Yuan & Marosszeky (13, 22) have measured the creep coefficient in compression and have used it in their repair model to estimate the relaxation in tension areas. They have, however, considered shrinkage uniform over the full thickness of the repair layer. With such simplifications, an acceptable evaluation of the long term cracking pattern (location, width and depth) of weather exposed structures can not be obtained.

Concrete is a visco-elastic-aging material. In the case of concrete repairs, shrinkage is an imposed strain (not an imposed stress), and the viscous behavior should correctly be termed "relaxation", even if the term "creep" is often used. The practical problem is that the curve in Figure 1 showing the stress after creep relief corresponds to the integration over time of the effect of a continuously increasing hygrally induced strain which, because of the humidity gradient that develops, can not be obtained directly from any simple laboratory test.

In fact, the real problem is that the mechanisms of creep and relaxation are still not completely understood. The most obvious part of this problem is Pickett's paradox (42, 43). As shown in Figure 4, the creep measured on a drying specimen can be more than 4 times that of a saturated sealed specimen (24), but the creep of a dry specimen is almost negligible. Thus, the creep behavior of drying concrete cannot be assessed using values obtained from specimens stabilized at different internal R.H. values. Presentlly, only empirical equations have been proposed to quantify the global creep behavior. Even the existence of drying creep is controversial, and various authors have proposed different explanations for the same physical evidence (44-47).

In the case of repairs, restrained shrinkage induces tensile stresses in the new concrete, but little is known about creep or relaxation of concrete in tension (48-50). Since cracking is often reached under fully restrained conditions, it is clear that the tensile stress can reach up to 100% of the tensile strength. It is not clear if the relaxation at high tensile stresses is still linear and this questions the validity of using the superposition principle for a time-dependent analysis (51). To add to the difficulty, the experimental study of concrete relaxation is time-consuming and requires sensitive servo-controlled equipment (some data indicate that relaxation occurs more rapidly than creep, but this has yet to be clearly established). Fundamental and clear data on the creep and relaxation in tension at high stress levels are definitively needed to properly analyze the strains and stresses in repaired layers.

Stress Relaxation by Cracking. When the tensile strength is exceeded at a given location, cracking occurs. This relieves part of the stresses, but these newly formed discontinuities in the matrix modify the stress distribution in the material. Subsequent strains and stresses can thus concentrate at crack tips and promote crack growth. Precise evaluation of cracking is not a simple task, but it is pertinent because it can also be used to evaluate the reduction of the protection that is expected from the repair layer. One interesting possibility is to use a damage parameter that reduces the effective modulus of elasticity in overstressed locations (52). Some on-going studies are trying to relate the damage level with important properties such as permeability to water or chlorides (53).

Conclusion

Having discussed the various aspects of the problem, it should now be asked if it is possible, in the present state-of-the-art, to develop a realistic model for concrete repairs. The honest answer is probably "not yet", even if such a goal is not beyond our reach. The main problem with concrete repairs is their small scale compared to the usual large structural elements which are normally analyzed. In view of this, it can be stated that three main obstacles must be tackled:

1) The steep humidity gradient within the "*critical thickness*" plays a significant role in the repaired layer and cannot be ignored when the strains and stresses are being calculated. This seriously complicates the numerical modeling, because the humidity profile and the hygrally induced strains must be determined with sufficient accuracy.
2) The lack of knowledge concerning the tensile creep and relaxation of concrete is problematic. In a first step, the model for a given repair could be based on experimental relaxation data obtained from an experiment specifically designed to reproduce the repair problem under study. With the accumulation of data on the different types of concrete and on the influence of the environmental conditions, it should be possible eventually to propose a more global approach for modeling tensile time-dependent behavior.
3) The stress relaxation by shallow cracking at the surface definitively modifies the stress distribution in the repaired layer. With the actual knowledge, correct modeling of strains and stresses in the first few millimeters from concrete surface is not a realistic goal. Fortunately, most concrete (not mortar) repairs are thicker than 50 mm, and this helps to reduce the overall influence of the lack of accuracy at the very surface level.

There is still a fair amount of work to be carried out to generate a better understanding of the time-dependent tensile behavior of concrete. However, to accelerate the progress towards an operational numerical model, it is essential to work simultaneously on the experimental and the numerical aspects of the problem. Since experimental programs dealing with relative humidity, shrinkage, creep and relaxation are time and money consuming, they should be planned only after the numerical obstacles have been clearly identified and all possible strategies have been weighed. This is the only way to insure that every bit of knowledge generated by costly physical tests will help to fill the gaps in an evolving numerical model. That is a long term approach but a winning one and a collaborative project linking the Laval University and the Institute for Research in Construction is actually ongoing.

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