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Compatibility of Repair Systems for Concrete Structures

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1. Introduction

Repair actions correct existing deterioration or distress of a structural, serviceability, or aesthetic nature, accomplishing restoration of structural integrity and serviceability, or correcting cosmetic defects. Structural repair restores lost strength or monolithic properties to damaged concrete members while serviceability repairs restore concrete surfaces to a satisfactory operational standard. Cosmetic patching restores concrete to a more pleasing appearance.

In major rehabilitation of structures many patch repairs are of a scale where structural integrity becomes significant and it is necessary to ensure the transfer of load from the concrete substrate into the repair materials and back into the concrete again. With such repairs problems may arise fairly quickly because of the difference in properties between the repair system and the concrete substrate. Table 1 illustrates the typical differences in some of the more important short term mechanical properties of repair materials.

TABLE 1 - Typical Mechanical Properties of Repair Materials

Property	Resin Mortar	Polymer modified Cementitious Mortar	Plain Cementitious Mortar
Compressive strength (N/mm^2)	50 - 100	30 - 60	20 - 50
Tensile strength (N/mm^2)	10 - 15	5 - 10	2 - 5
Modulus of elasticity in compression (kN/mm^2)	10 - 20	15 - 25	20 - 30
Coefficient of thermal expansion (per °C)	$25 - 30 \times 10^{-6}$	$10 - 20 \times ^{-6}$	10×10^{-6}
Water absorption (% by weight)	1 - 2	0.1 - 0.5	5 - 15
Maximum service temperature (°C)	40 - 80	100 - 300	> 300

(Mays and Wilkinson - Ref.13)

These differences can be categorized as follows.[1-3]

- Curing shrinkage of repair material relative to drying shrinkage of the concrete substrate.
- Differential thermal expansion/contraction between the repair material and concrete substrate.
- Differences in stiffness and Poisson's ratio causing unequal load sharing and strains resulting in interface stresses.
- Creep of repair material under sustained load as compared with that of the concrete.
- Relative fatigue performance of the components in the composite steel-concrete repair structures.

Such differences in properties may result in either initial tensile strains induced in the repair or cracking at or adjacent to the repair substrate interface . Both of these may reduce long-term structural capacity. Stresses that may be generated by relative volume changes between the repair material and the existing concrete substrate and service loads carried by the repair are shown in Figure 1.[4]

During service, incompatibilities in the form of differing elastic moduli and differential thermal movement between repair and substrate can cause problems. Also, creep of the repair material under sustained stress may render the repair less effective with time. The effects of carrying out repairs while the existing structure is under load and the influence of cyclic and impact loading may also be significant, and failure to support some of the load temporarily before and during the repair process will result in stresses being transferred to undamaged parts of the member. Little load will be subsequently transmitted through repaired areas making the repair non-structural. Figure 2. shows how load relief during the repair operation may enable the repair material to carry its share of stress.

Many of the commercial systems available for concrete repair can be conveniently categorized in the generic systems shown in Table 2.[5] Most are general formulations for cosmetic use and for corrosion control. They are likely to have poor structural characteristics and are ill-matched to the concrete. Consequently, they may not be durable and are likely to crack or delaminate due to excessive long term thermal and shrinkage movements.

TABLE 2 - Generic Systems for Concrete Patch Repair

Resinous Materials	Polymer Modified Cementitious Materials	Cementitious Materials
A: Epoxy mortar	E: SBR modified	J: OPC/Sand mortar
B: Polyester mortar	F: Vinyl acetate modified	K: HAC mortar
C: Acrylic mortar	G: Magnesium phosphate modified	L: HAC/OPC mortar mixtures
D: Polyurethane	H: Acrylic modified	M: Expansion producing grouts
	I: Ethyl Vinyl Acetate	N: Flowing concrete

(Emberson and Mays, Ref. 5 Modified)

Pre-repair considerations are as important as the repairs and consequently proper materials selection and surface preparation are essential to high quality, durable, and functional repair. Materials selected for use in concrete repair must meet specification requirements for the particular application or intended use. Engineers therefore need to know the mechanical and physical characteristics of available products and their proposed substrates before an assessment of structural compatibility can be made and suitable repair systems chosen.

2. Compatibility

Compatibility for a structural repair may be defined as that combination of properties and dimensions which ensures that interface bond strength is not exceeded and that the repair material carries its design load.[6] This definition involves a knowledge of repair dimensions in conjunction with a variety of material properties of both the repair material and substrate and as well, knowledge of the environmental influences and applied structural loads and resulting deformation.

Repair materials can be formulated to provide a very wide range of properties from brittle to ductile and impermeable to porous.[7,8] A wide variety of combinations of these properties is possible, with values selected to meet specific requirements of the application at hand. Many products particularly polymer-based materials are influenced by environmental conditions in service. In the repair situation environmental conditions can range from freezing to refractory temperatures and from very dry to full saturation. While cement-based materials are slightly affected by these conditions, the polymer-based materials are significantly affected.[7-9] Therefore, the selection of the appropriate material is imperative to the intended purpose. Table 3 suggests the properties generally required of repair materials as compared with the concrete substrate, to produce long-term structurally efficient repairs.[5]

TABLE 3 - General Requirements of Patch Repair Materials for Structural Compatibility

Property	Relationship of repair mortar (R) to concrete substrate (C)
Strength in compression, tension and flexure	$R \geq C$
Modulus in compression, tension and flexure	$R \sim C$
Poisson's ratio	Dependent on modulus and type of repair
Coefficient of thermal expansion	$R \sim C$
Adhesion in tension and shear	$R \geq C$
Curing and long term shrinkage	$R \leq C$
Strain capacity	$R \geq C$
Creep	Dependent on whether creep causes desirable or undesirable effects
Fatigue performance	$R \geq C$
Chemical reactivity	Should not promote alk/agg reaction, sulphate attack or corrosion of embedments in substrate
Electrochemical stability	Dependent on permeability of patch material and chloride ion content of substrate

(Emberson and Mays, Ref. 5 Modified)

To understand how various factors affect the performance of repair systems it is necessary to consider the repair and substrate as components of a composite system, which includes dissimilar materials. The meaning of compatibility in such a system relates to a balance of physical, chemical and electrochemical properties and dimensions between repair materials and substrates. These ensure that a repair withstands stresses induced by volume changes, chemical and electrochemical effects without distress and deterioration in a specified environment over a designated period of time. Figure 3 present the various factors affecting the compatibility of materials[4] and these are discussed in detail below.

2.1 *Dimensional Stability*

Dimensional incompatibility adversely affects the load carrying capacity of structural repairs. It may lead to the inability to carry the expected portion of the load and overstressing in the existing structure.

The two volume-change properties that affect dimensional compatibility are drying shrinkage and thermal expansion.[9-14] When making large thick patches or when placing an overlay, it is important to closely match the coefficient of thermal expansion of the repair material with the concrete being repaired. The differences in volume change that arise when a composite of two materials with quite different thermal coefficients undergo a significant temperature change, often cause failure at the bond interface or within the section of lower strength material.[14-17]

2.2 *Modulus of Elasticity*

When materials with widely differing moduli are in contact with each other, the significant difference in deformability will cause problems under specific loading conditions. For example when the external load is perpendicular to the bond line (Figure 4-a) as in the case of pavement repair, a difference in modulus of elasticity between the repair material and concrete is usually not a problem. In repairs where the service load is parallel to the bond line however, the deformation of the lower modulus materials transfers the load to the higher modulus material which may then fracture. (Figure 4-b).[4,7]

Not all failures of bonded materials with widely differing modulus of elasticity are caused by external loads. Shrinkage or thermal expansion and contraction can cause loss of bond unless the modulus of the repair material is low enough to permit movement without excessive stress at the bond line.

2.3 *Chemical Reactivity*

The reactivity of the patching material to steel reinforcement and other embedded metals, to the aggregate in the concrete or specific sealers or protective coatings applied over the patch must also be considered. Patching materials with low to moderate pH provide little protection to concrete while highly alkaline material may attack potentially reactive aggregates in the concrete. Therefore reactivity of patching materials with both the substrate and the surface protection product should be checked.[7]

2.4 *Electrochemical Compatibility*

The resistivity of the patching material may also affect the durability of the patch and the concrete in the members undergoing repair. Materials that are highly resistive or non conductive have a tendency to isolate the repaired area from the adjacent undamaged areas. Consequently, if there is a large permeability or chloride content differential between the patched area and the rest of the concrete, the corrosion current becomes concentrated in a restricted area and the rate of corrosion may then be accelerated, causing premature failure in either the patch or adjoining concrete. This is illustrated in Figures 5 & 6.[18,19]

Compatibility cannot however, be tackled purely in material terms. It must factor in aspects of design detailing and construction.[20,21] Several interrelated items such as surface preparation, method of application and inspection need to be considered to ensure long-term performance. Figure 7 highlights the critical factors that largely govern the effectiveness and durability of concrete repairs in practice and must be considered in the design and specification process.

3. Research to Date

Specifications for repair materials and techniques draw upon the experience of the engineer and depend upon an understanding of the performance and data available in support of a particular material or system. Available data however, is meager, fragmented and very short-term, and highly defined in one area and poorly defined in others. Most of the research done to date and now underway is related to studies in 3 main areas: durability of the bond between new and old concrete or repair materials and mature concrete, behavior of polymer materials in repair, and electrochemical compatibility.

3.1 Polymer-based Materials

Polymer-based materials are usually innovative and do not conform to the conventions prescribed in codes and in National Standards.[22] Sprinkel (1981) reported on the debonding of polymer concrete overlays due to thermal incompatibility between the overlay and the concrete bridge deck. A basic mismatch of the unique physical properties with those of traditional construction materials was identified by Hewlett and Hurley 1985. These researchers cautioned that in the design and use of polymers the response of the composite (not the isolated polymer) to the service environment needed to be assessed.

Several authors have identified the potential importance of property mismatch between polymer-based patch repair materials and the reinforced concrete substrate. Plum (1990 and 1991) investigated the behaviour of polymer materials in repair applications and the factors influencing their selection. His work highlighted the sensitivity of polymers to environmental conditions during the curing phase and in service. He noted that while cement based materials are slightly affected by these conditions, polymer materials are significantly affected. This was corroborated by Browne and Robery (1992) in their study which attempted to quantify coating performance.

3.2 Structural Compatibility

Little attention has been paid to the structural implications of property mismatch between repair materials and the substrate reinforced concrete. Some of the more important investigations are as follows. May and Wilkinson (1987) studying the influence of polymer repairs on structural performance, identified effects on the load bearing due to differences in properties between the materials.[13] The inability to share the load was attributed to differences in moduli, creep and thermal coefficients.[23-25]

Plum (1990) presented a theoretical study in which he matched a group of mechanical properties of polymers to the type of repair application, viz. structural (i.e. stress carrying ability) or cosmetic (i.e. more protection and finish). Using the range of material properties determined for nine generically different systems Emberson and Mays (1990) developed two and three dimensional linear elastic finite element models to elucidate axial load transfer through simple patch repair in reinforced concrete members.[25] Marosszeky (1989) investigated the stress performance in repaired members under field conditions.

3.3 Electrochemical Compatibility

Electrochemical effects of repair on an existing structure are poorly understood. Hime and Erlin (1986) were among the first to identify potential problems arising from the use of high density low permeability patching materials.[18] They presented chemical mechanisms to explain half-cell potentials and causes for chloride-induced corrosion. Subsequently, members of RILEM Committee TC-185, Raupach, Schisel, Andrade and Mailvaganam (1991) working on the effects of proprietary repair materials and rendering mortar used in cosmetic (protective) application highlighted the accelerated corrosion that resulted from the use of impermeable patches. More recently Gu et al (1994) using electrical impedance techniques have corroborated these findings by studying the effect of uneven porosity distribution in repair mortar on corrosion of steel. The low frequency impedance technique was used to determine the loci of the corrosion reactions.[19]

3.4 Bond Durability

Several studies are underway to investigate the long term durability of repaired structures.[26-31] Most have focused on the factors influencing bond development, strength, and time dependent properties which govern load bearing capacity. Marosszeky (1989) as noted before, studied bond development in repaired members[31] and evaluated important properties of repair patching materials which can affect the bond of a repair such as shrinkage, thermal movement, compressive, shear and tensile strength. Subsequent work by the same author (1991) highlighted stress development in repair situations and introduced the concept of "stress performance margin", (the extent by which the strength of a material exceeds maximum induced stresses). Yvan and Marosszeky (1991) investigated the influence of early age properties of 3 polymer-based repair material or load bearing abilities under different environmental conditions.[24]

Factors affecting the bond between new and old concrete was determined by Wall and Shrive (1988) and a method of testing for bond which reflected typical in service stress state was proposed.[26] A major study of the durability of new to old concrete was conducted by Pigeon and Saucier (1991 and 1992).[28-31] The principal parameters investigated in the first study were the composition of the bonding agent and saturation of the base concrete. The subsequent study investigated the influence of the type of cement used on the microstructural characteristics of the interface. A more detailed examination of the interface microstructure was conducted by Carles-Gibergues et al (1993).[32] The results showed that the nature of cement and especially its sulfates, is a main factor in the microstructure formation of the bonding zone.

3.5 Repair Practice

A contractors viewpoint was presented by Emmons and Vaysburd (1993) who emphasized the fragmented nature of the research done to date.[4,21] They contended that the value of data produced from the study of one variable at a time, was rather limited because the behavior of repair systems in structures was a result of interaction between many variables acting simultaneously. A holistic approach was proposed by these authors and Mehta (1993). The term 'holistic' refers to an understanding of a phenomenon or a structure in terms of an integrated whole, whose properties cannot be deduced from the sum of the properties of the constituent parts. The holistic model suggests that to achieve durable repairs it is necessary to consider the factors affecting the design and selection of repair systems as parts of a whole or as components of a composite system.[33,34]

4. Current Research on Repairs at IRC

IRC has recently started a research project with the objective of making a significant contribution to the understanding of how and why repairs work (or fail) and ultimately to model and extend their service lives. The research is focused on compatibility of repair and substrate and is based on fundamental measurements, in the laboratory, initially with small, then with larger specimens, and later in the field. The data collected will be used to develop analytical techniques for predicting and extending the durability of repairs. Team members are studying the structural effectiveness of systems and materials (polymer- and cement-based) currently used in the repair of concrete and will ultimately be able to prescribe improvements. Two major lines of investigation have been started, one on electrochemical compatibility and the other on structural/mechanical compatibility of repairs to reinforced-concrete structural members.

4.1 Electrochemical Compatibility

When a difference in electrical potential exists between two areas of a steel-reinforced concrete member, corrosion may occur. In this paper an experiment is described in which two causes of corrosion are investigated. The first is due to differing oxygen concentrations at adjacent locations which result in the creation of a galvanic cell and corrosion of the steel. The second is more familiar and is due to differences in chloride ion concentration at adjacent locations which also creates a cell. In this experiment 300 x 340 mm concrete slabs 75 mm thick are cast with a 50 x 50 mm steel mesh (3 mm dia. wires) at the half depth (Fig 8). At the centre of each slab is a 125 x 125 mm x 50 mm deep hole with the steel mesh exposed 12.5 mm above the bottom of the hole. After the surrounding slab has been cured for 28 days the hole is 'patched' with a more impermeable repair mortar and cured for another 28 days. With time the oxygen diffuses to the steel mesh in the surrounding concrete but not at the same rate through the less porous patch. The oxygen deficiency in the central patch creates an electrical potential with the steel in the patch becoming the anode and rusting. The contours of potential differences as measured by half cell potential are shown in Fig. 9.

In the second series of experiments the same setup is used but this time the concrete surrounding the 'hole' is contaminated with chloride. The patch concrete which is of the same porosity as the surrounding concrete is not chloride-contaminated and therefore an electrical potential is created as shown in Fig. 10. The surrounding concrete is the anode and the chloride ions in this region attack the passivation layer on the steel mesh and cause pitting.

4.2 Structural/Mechanical Compatibility

Research on structural/mechanical compatibility has just begun with the important factors having been identified in Table 3. As noted earlier, the literature describes advances in assessing the influence of some of these factors, taken singly, on the surface strains of the repair and substrate. A great deal more information of compelling interest would be available if strains could be measured *within* the repair or substrate near or at the interface between the two. Some early effort is being spent on this pursuit but internal measurements affect the results they record to some, as yet ill-defined extent. Continuous internal and external temperature measurements will be made as a matter of course.

Some pilot tests of continuous cantilevered beams and slabs which include extensive instrumentation are being designed. Patches will be applied in tension/shear zones, in some cases, and in others, in compression/shear areas (Fig 11). The beams will be subjected to strain measurements under load before repairs are made, while repairs are curing and after they have reached 28-day strength and stiffness. Most of the factors in Table 3 will be investigated, included extremes of temperature, for patches made using commercial repair materials. Some repair and

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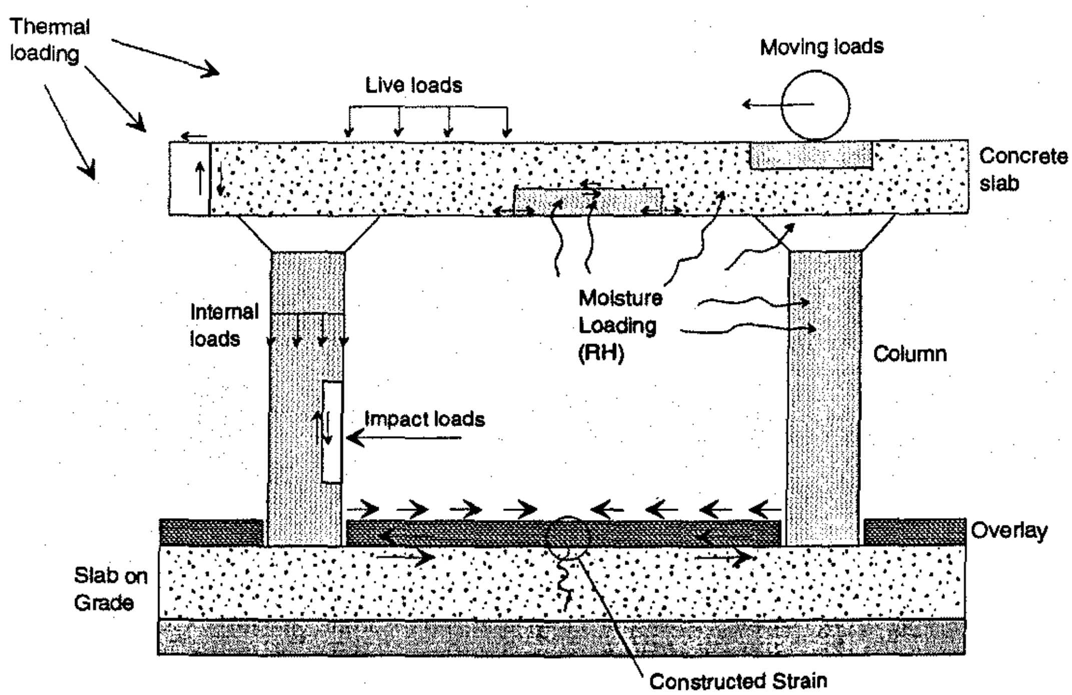

Fig. 1 Possible Loads Acting on a Repair (Idealized)
(Emmons & Vaysburd Ref. 5)

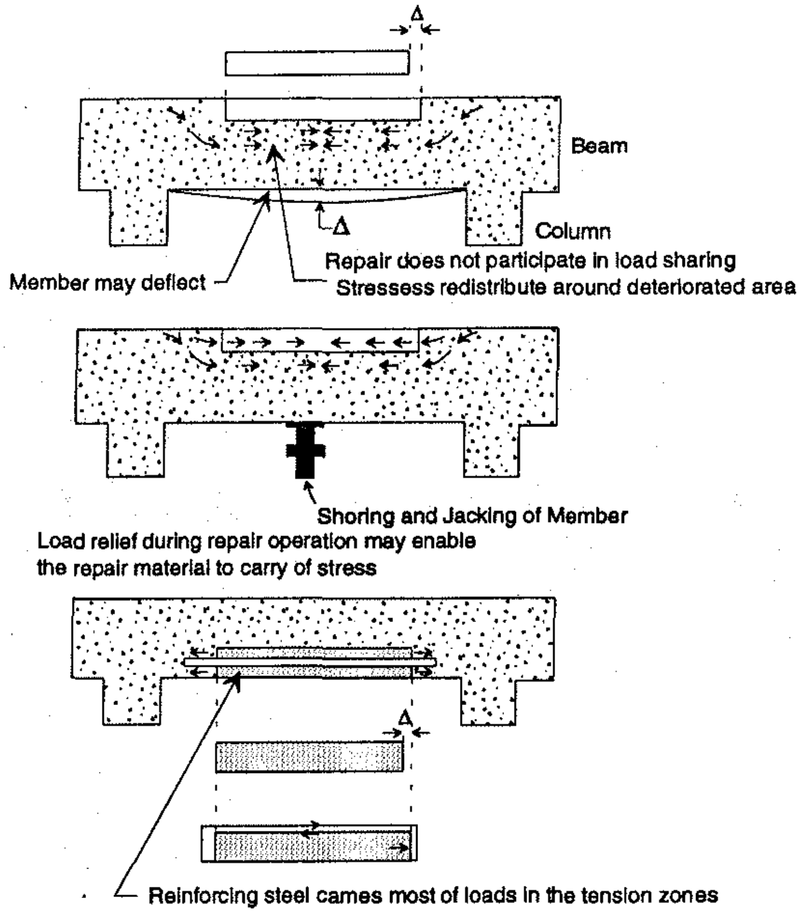

Fig. 2 Repair in Compression & Tension Zones
(Emmons & Vaysburd Ref. 5)

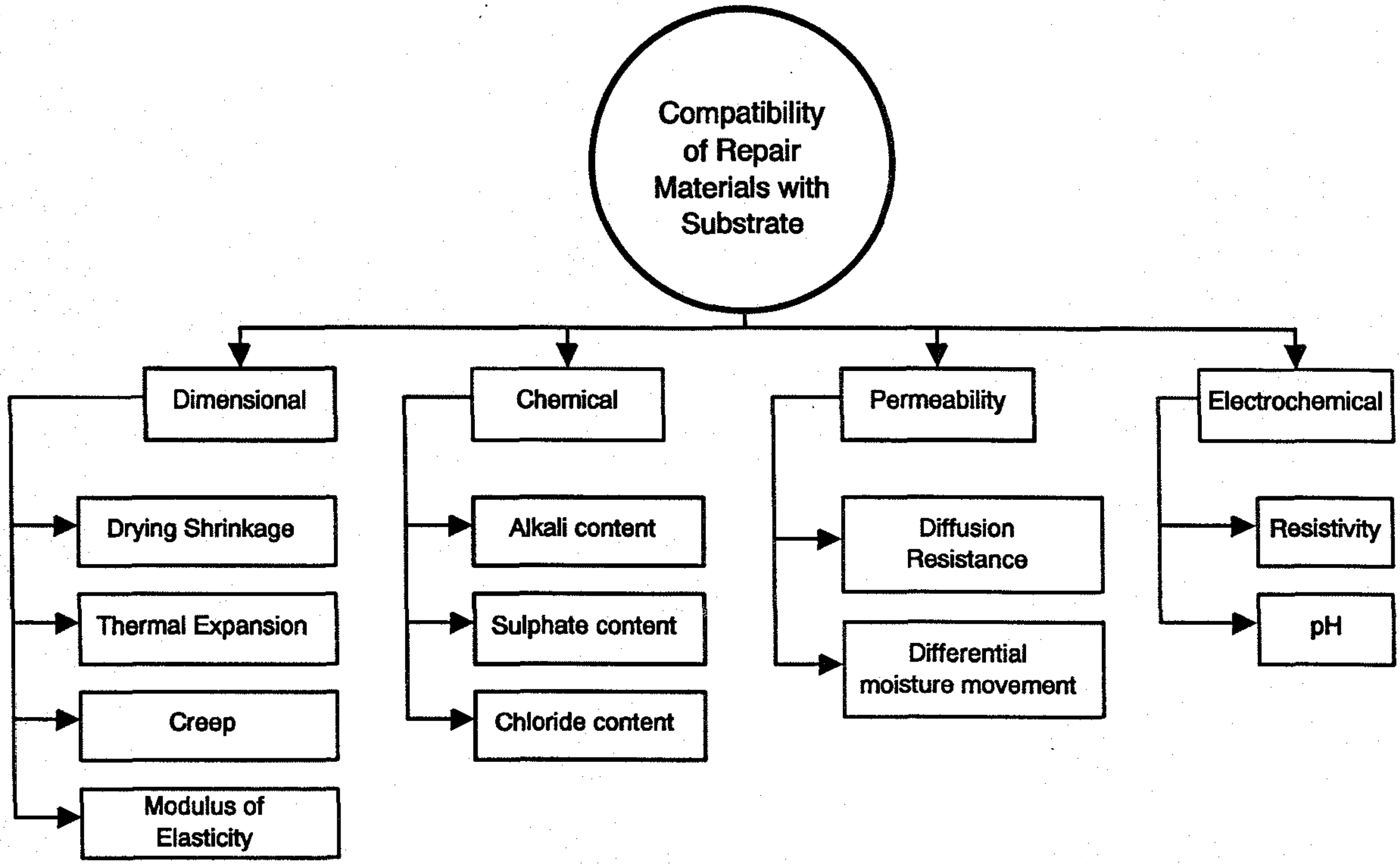

Fig. 3 Various Factors Affecting the Compatibility of Materials
(Emmons & Vaysburd Ref. 5)

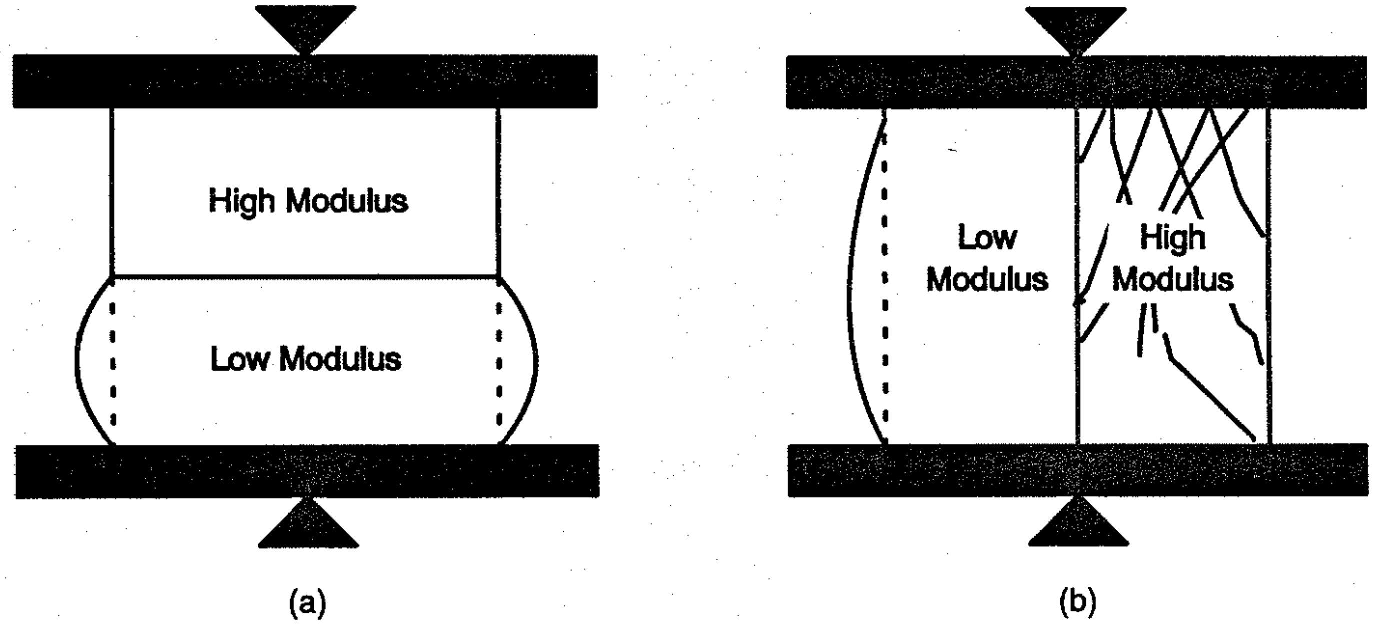

Figure 4. Materials with low modulus of elasticity deform more under given unit load. (From Warner, J., Selection of Repair Materials, *Concr. Constr.*, 8, 865, 1984. With permission.)

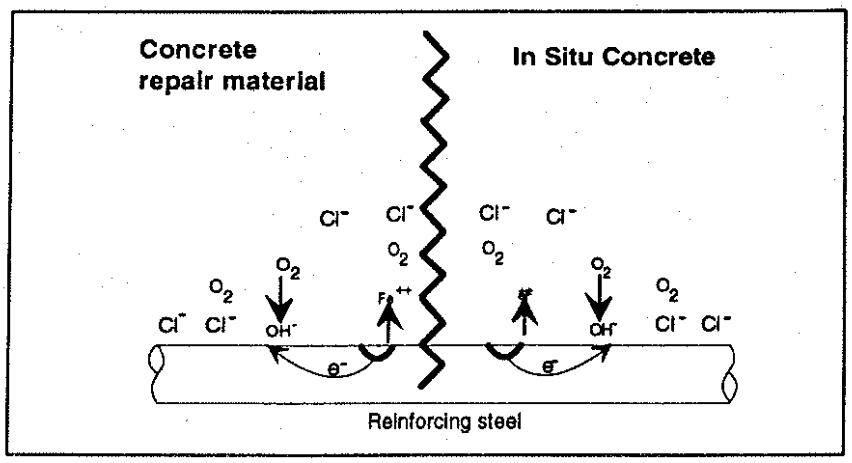

Fig 5 Initial stage; oxygen concentration the same in the repair material and the in-situ concrete

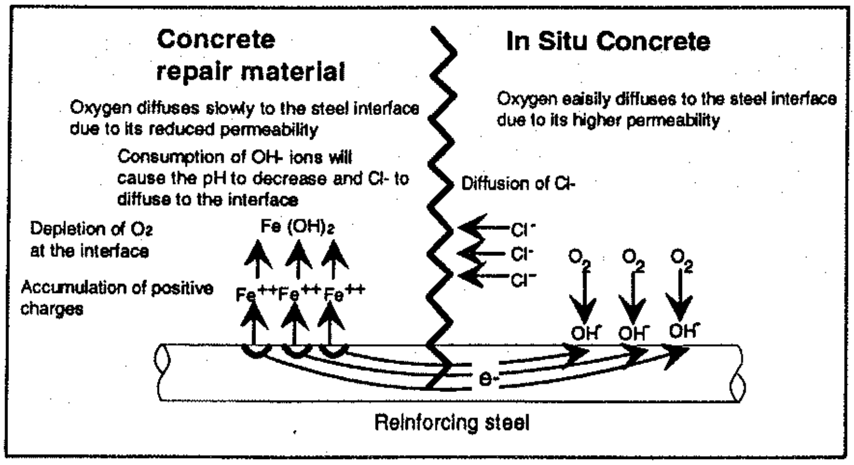

Fig 6 Increased corrosion where patch material is applied

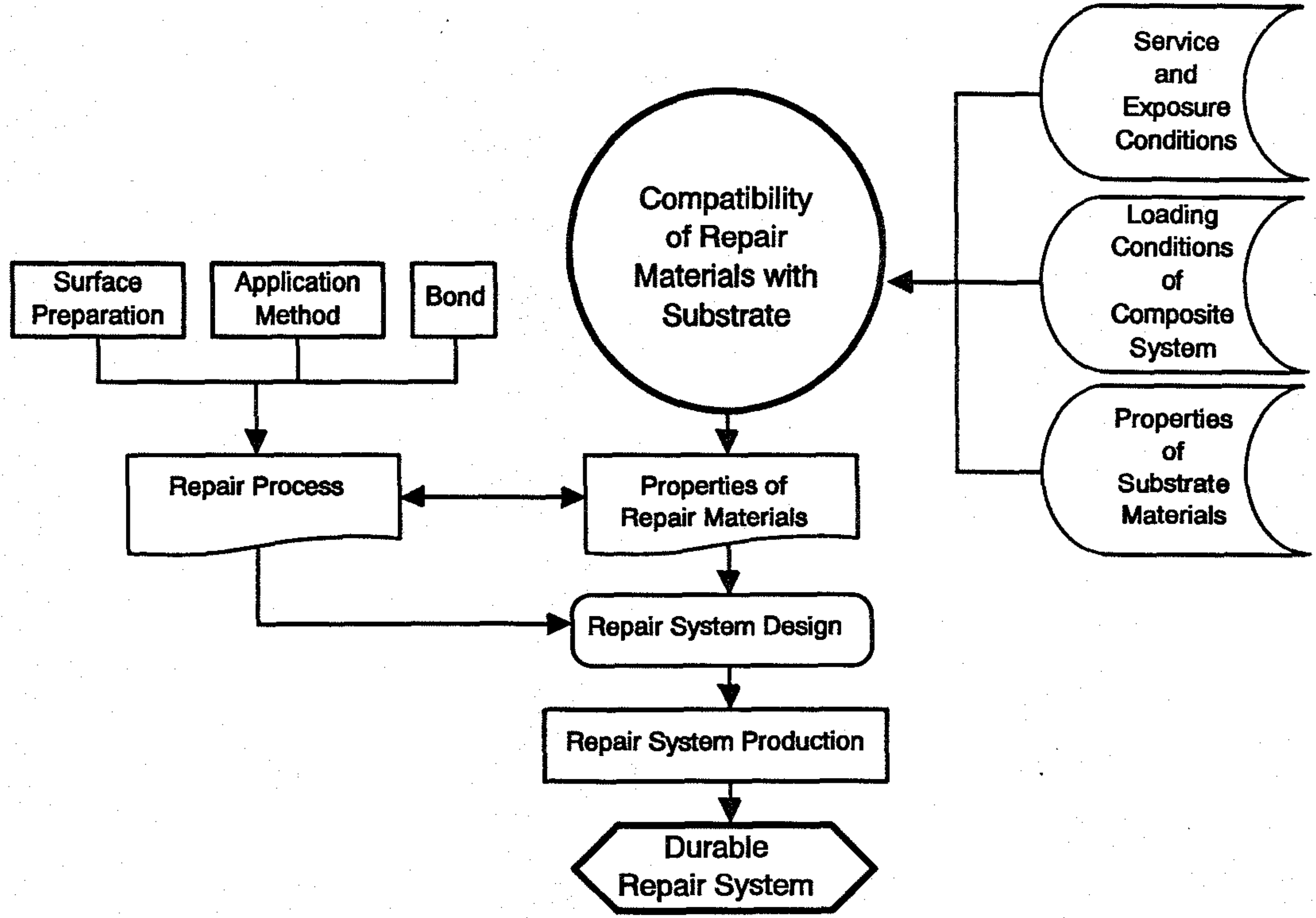

Fig. 7 Factors Affecting Durability of Concrete Repair Systems
(Emmons & Vaysburd Ref. 5)

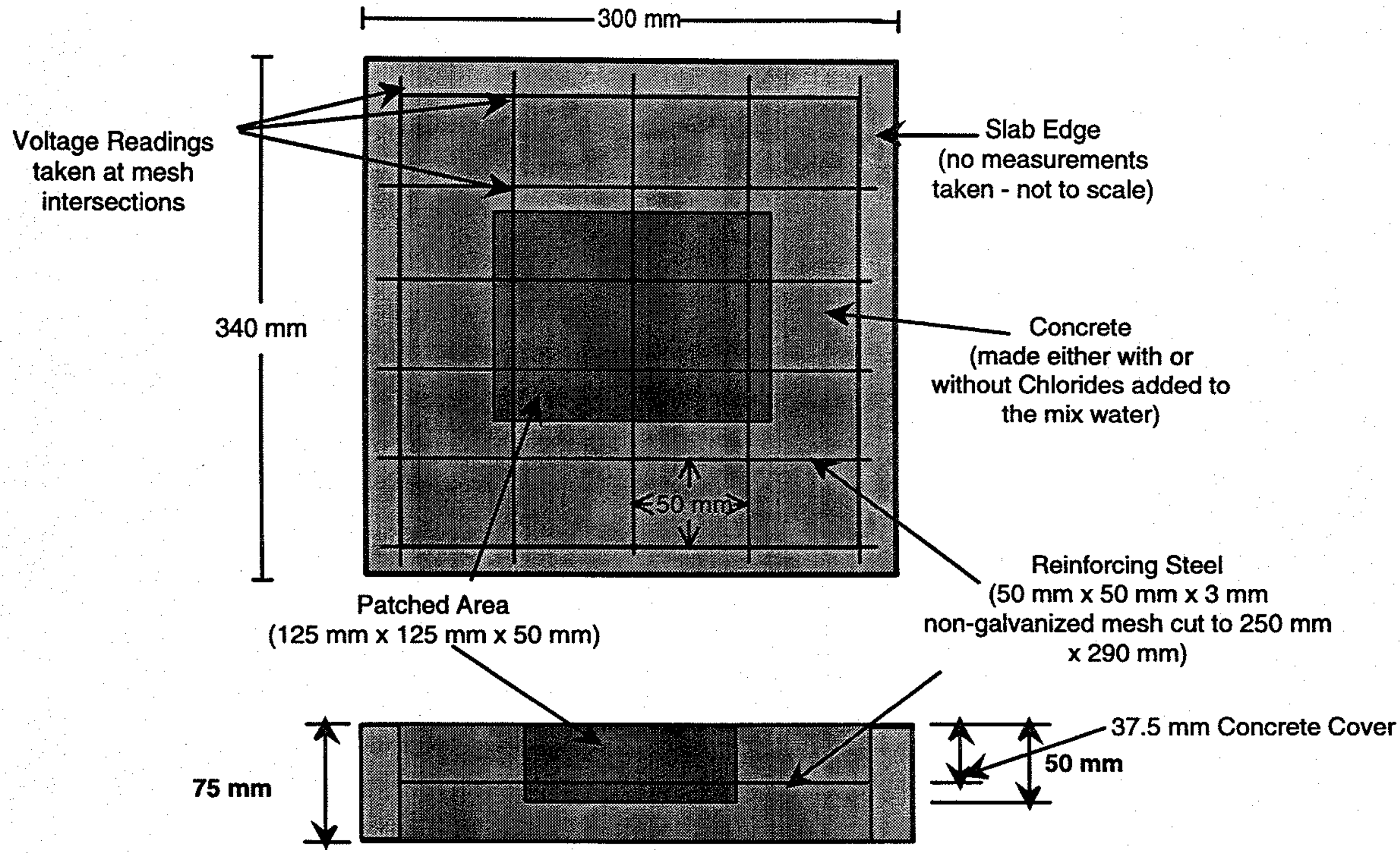

Fig 8. Sample Diagram for Half - Cell Potential Contour Maps

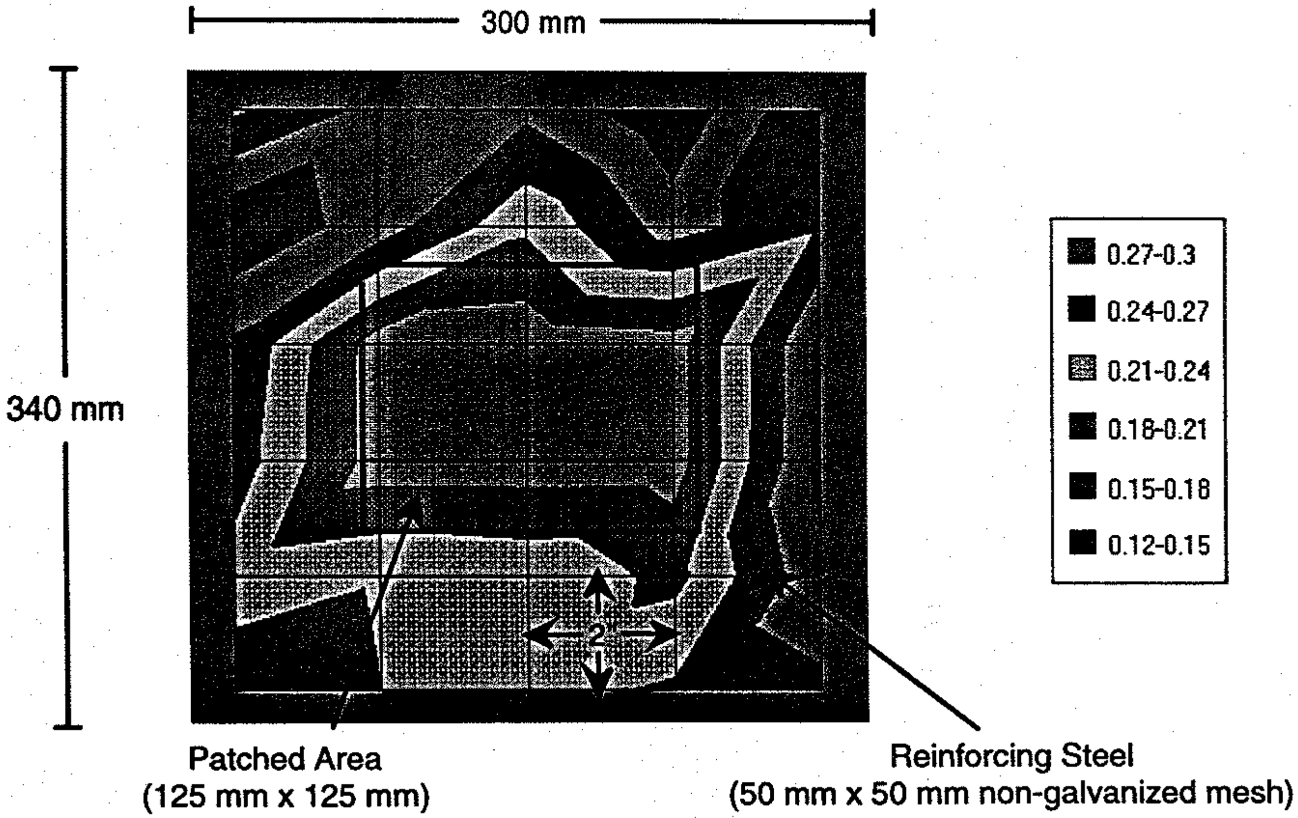

Fig 9. Half - Cell Potential Contour Map for Normal Concrete Slab Patched with Less Porous Proprietary Patching Material

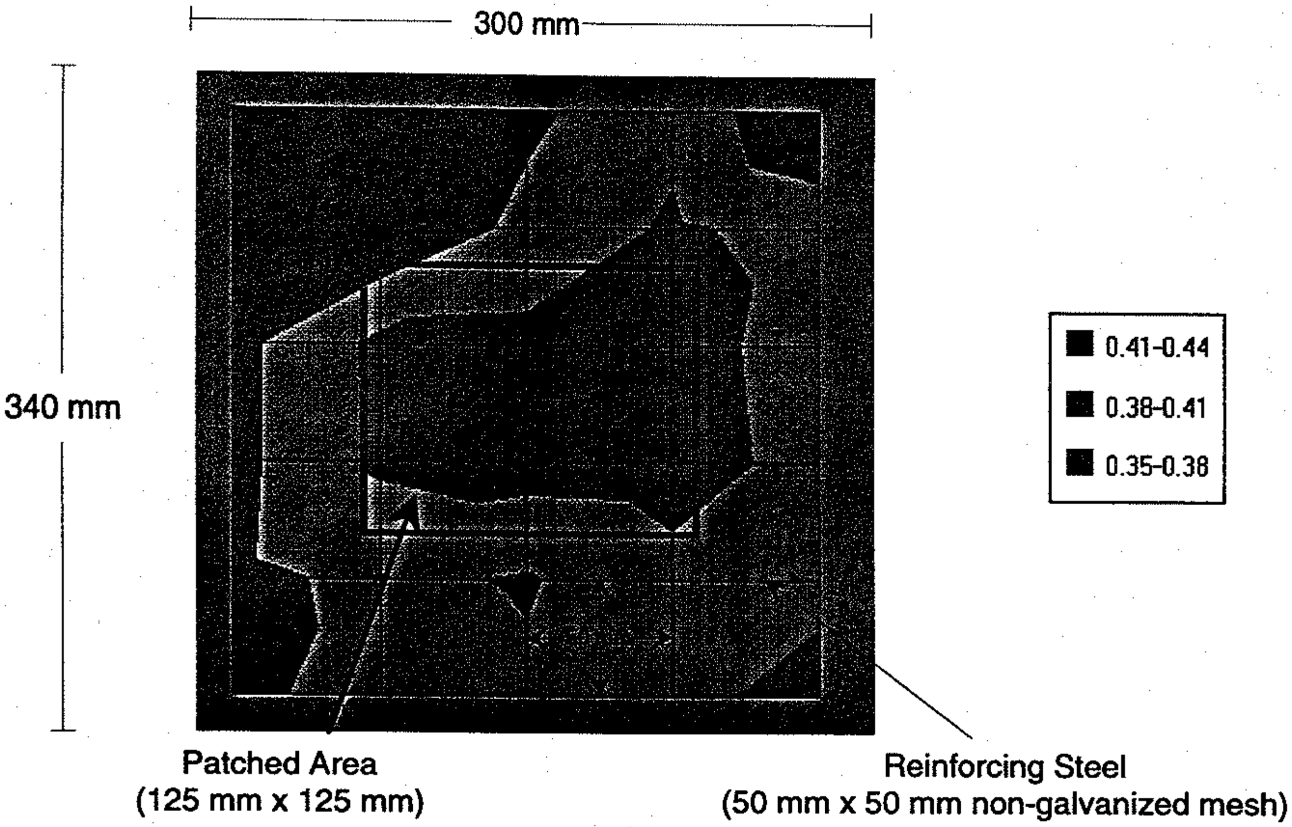

Fig 10. Half - Cell Potential Contour Map for Chloride Containing Concrete Slab Patched with Regular Mortar of the Similar Porosity to Concrete.

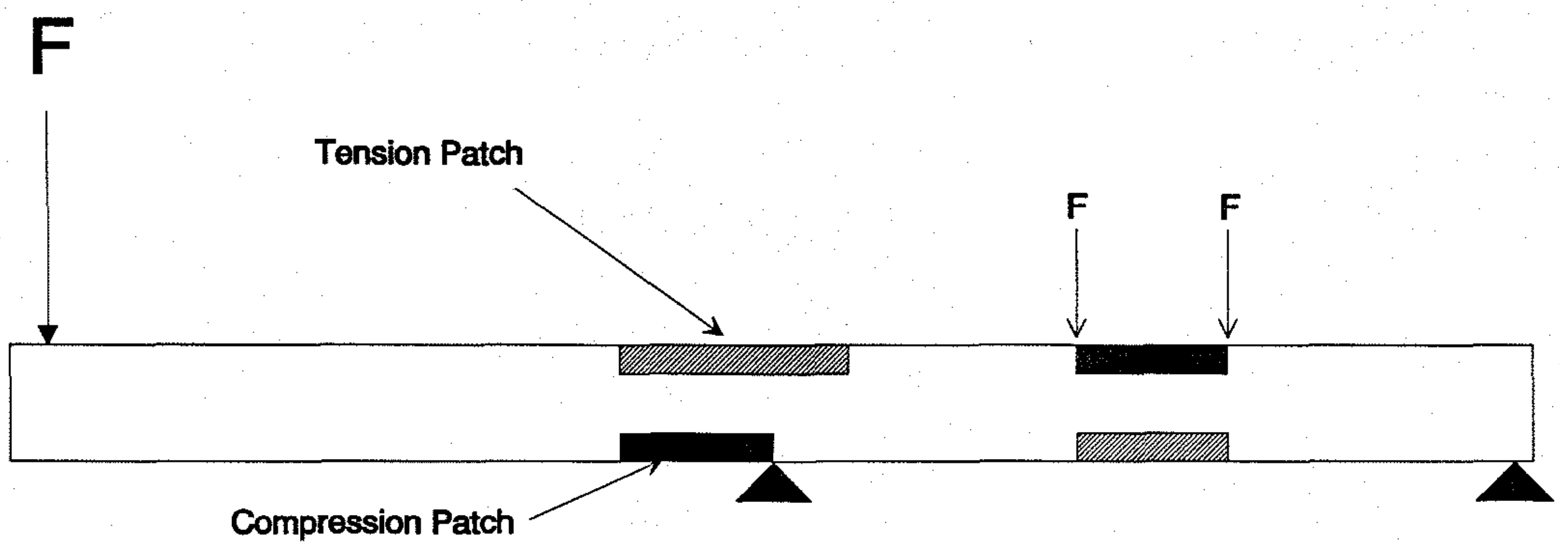

Fig 11. Pilot Beam/Slab Tests for Structural/Mechanical Compatibility Measurements

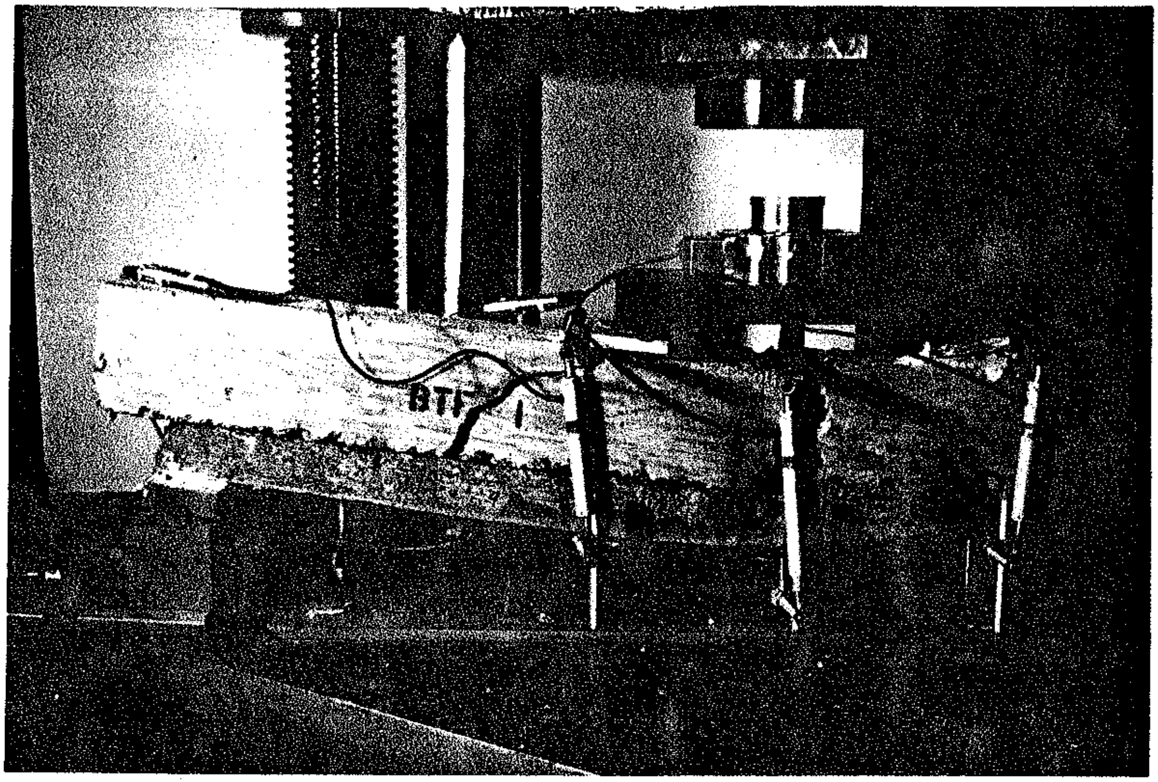

Figure 12

Photo showing effects of sudden delamination of tension patch just before failure.