# Photoelasticity and Its Use in the Study of Macrostrains in Concrete

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## INTRODUCTION

In an attempt to provide an experimental technique which would yield information within a fracture-mechanics frame of reference, this report describes an application of the principles of photoelasticity in the study of surface strains in plain concrete.

The behavior of a nonhomogeneous, nonisotropic, heterophase material, which adequately describes concrete, is a topic of current, general interest. The development of several new composite materials within this description has added impetus to the study of their basic engineering characteristics.

Historically, the strength properties of solids have been studied along two lines. The older, the phenomenological or gross effect, attempts to describe the reactions of a solid when acted upon by an external load system. The failure criteria are then postulated with the assumption that the solid is isotropic, homogeneous, and continuous. The second approach is mechanistic in nature. Here the properties are analyzed on the basis of inherent material failure characteristics. These theories are relatively new and are primarily concerned with why a material fractures at less than its theoretical strength. While strength theories describe alternate conditions for failure itself, fracture theories attempt to construct reasons for the beginning of failure and under what conditions fracture will progress.

The earliest work on the detection of microcracks in concrete was carried out by searching exposed faces of test specimens with a microscope during intervals between incremental loading. Past research has also determined a clear relationship between internal cracking and the shape of the stress-strain diagram.

Other techniques used in cracking studies include the use of x-rays, application of strain gages to the surface of concrete, and ultrasonic techniques. The latter methods have served to verify that cracking takes place long before concrete failure, and they allude to the origin of cracks and their propagating characteristics.

## Preparation of Specimens

The 32 concrete specimens for this project were selected in such a way that several variables could be monitored, including water-cement-ratio, maximum size aggregate, and aggregate dispersion in the paste matrix. A ½-inch-thick rectangular-shaped specimen was selected so that the response to load would be primarily of a plane stress nature and would yield more meaningful data where only a two-dimensional surface could be studied. The specimens were cut from standard 6-× 12-inch cylinders using a specimen cutting machine. Before application of the liquid photoplastic, the specimens were edged and lapped smooth with carborundum.

One side of each specimen was coated with a thin layer of reflective epoxy adhesive. Liquid photoplastic was then applied over the reflective adhesive, after the latter had hardened, to a thickness of from 0.1 to 0.2 inches. Arbitrarily, the photoplastic was discontinued about ¼ inch from the loading edges to reduce edge concentrations due to irregularities.

## Experimental Procedure

Strain measurements from the photoelastic coatings were made with a reflective polariscope consisting of a white light source, a plane-polarizer, a polaroid analyzer and quarter wave plates. The polarizer and analyzer were set at right angles to each other.

A brief review of the principles of operation might be in order here. As a high-intensity white light passes through the plane-polarizer, the rays are polarized into a single plane. As a polarized ray passes through the plastic on the strained specimen it is doubly refracted into two components, taking two paths at right angles to each other and traveling out of phase with each other. Their directions correspond to the two principal strains, $e_1$ and $e_2$. The two light rays are then reflected by the under adhesive coating to the analyzer, the movable portion of which is graduated to enable quantitative determination of the angles of inclination of the light rays.

The light rays reflected to the analyzer indicate black fringes at all points on the plastic where the direction of the principal strains coincide with the angle setting of the analyzer. A line of these black points is called an isoclinic and represents a locus of points along which the inclinations of the principal strains are constant.

At all points on the plastic other than those in the isoclinics, the light rays reflected to the analyzer are in colored patterns (reds, blues, greens, and yellows predominately). These colored patterns are called isochromatics and indicate the algebraic differences between the principal strains ($e_1 - e_2$). The magnitude at a given point is indicated by the particular color at that point and by the location of the point with respect to a tint-of-passage (or fringe order) between red and green. The isochromatics are easier to distinguish if the black isoclinic fringes are removed from the field, which is done by introducing quarter-wave retardation plates between the polarizer and the plastic and between the plastic and the analyzer.

The relative retardation, $D_s$, which exists between the two light waves as they emerge from the plastic is proportional to:

1. The difference between principal strains $(e_1 - e_2)$;
2. The distance the light travels through the plastic, $2t_p$;
3. The strain-optical constant for sensitivity, $k$; and
4. The correction factor that accounts for reinforcement effects of the photoplastic, $C$.

These effects can then be expressed jointly by:

$$D_s = 2t_p\ k(e_1 - e_2)\ C \qquad (1)$$

where $2t_p$ is used since the light passes through the plastic twice.

A reformulation of equation (1) gives the Fringe Value, $f$, in psi, i.e., the principal stress difference represented by each succeeding tint-of-passage:

$$f = L/2t_p\ k \qquad (2)$$

## Testing Procedure

The thin rectangular specimens were compressed in an Instron Universal Testing Machine. To allow sufficient time for a more thorough examination of photoplastic color patterns and to minimize creep within the concrete, 35-mm color slides, using a single-lens reflex camera, were taken of each specimen as it was loaded to failure. The typical photography sequence included the isochromatic fringes at each 1000-lb. load increment with several pictures of isoclinic patterns at different angular rotation of the analyzer. Loading and photography continued until failure occurred.

As the fringe order progressed beyond the 5th fringe the tint-of-passage became increasingly difficult to discern. However, the sequential photographic record permitted their interpretation and defining sometimes up to the 8th order.

## Test Results

The isoclinics give the principal stress directions in a form which is generally not directly usable. Consequently, the usual procedure is to present the principal stress directions in the form of isostatics, or stress trajectory diagrams, where the principal stresses are normal and tangent to the isostatic lines at each point. The isostatic diagram is obtained directly from the composite isoclinic pattern by connecting points, oriented to the respective principal stresses (or strains), in the several regions to form a continuous line.

The foregoing procedure was applied to the isoclinic patterns of several specimens from two groups, one where only one or two aggregates were included in a specimen and two, for regular concrete specimens. The strain trajectories were considerably distorted from those which are found in uniform compression fields.

Study of the patterns formed by the isochromatics, isoclinics and isostatics produced the following observations: first, both the isochromatics and the isostatics show stress concentrations at the aggregate-paste interface indicating that the bond point between the two materials is straining excessively; second, it appears that the difference in the moduli of elasticity of the mortar and the coarse aggregates is sufficient to warrant more consideration in mix design; third, while the photoelastic process is incapable of demonstrating the entire picture of stress effects in a material, it nevertheless has shown the existence of regions in which the microscopic stresses are undoubtedly increased due to the imposition of excessive macro-level stresses; fourth, the stress trajectories demonstrate the fact that even in relatively small pieces of concrete, subject to uniaxial force, there exist many regions in complex stress conditions. This, in turn, demonstrates the need for defining a failure concept which can account for fracture under every possible load condition because, in truth, each condition does exist in concrete.

In order to relate the photoelastic effects of one concrete to another, a common parameter is required. The fringe order of magnitude is most useful for this purpose, but must be stated in terms of relative imposed loads. The stress concentration factor, $K$, may be used to make this comparison and is defined as:

$$K = (S_1 - S_2)/S_{ave} \geq 1$$

where $S_{ave}$ is the applied load divided by the cross-sectional area of the specimen. The principal stress difference, $S_1 - S_2$, is obtained directly by noting the fringe order at the point in question and multiplying it by the fringe value (in terms of stress). An average value of the stress concentration factor was calculated for each of 32 specimens in this program.

A comparison of aggregate size and $K_{ave}$ yields a most interesting result. When the values of $K$ were averaged for both regular concretes and single and/or double aggregate specimens, it was observed that as the maximum aggregate size decreased, the highest observable fringe order also receded. These values are plotted in Figure 1, and clearly demonstrate the elevated stress concentrations due to an increase in the maximum size of the aggregate in the concrete.

## SUMMARY

In conclusion, the general observations made from viewing all concrete specimens tested with photoelastic coatings are:

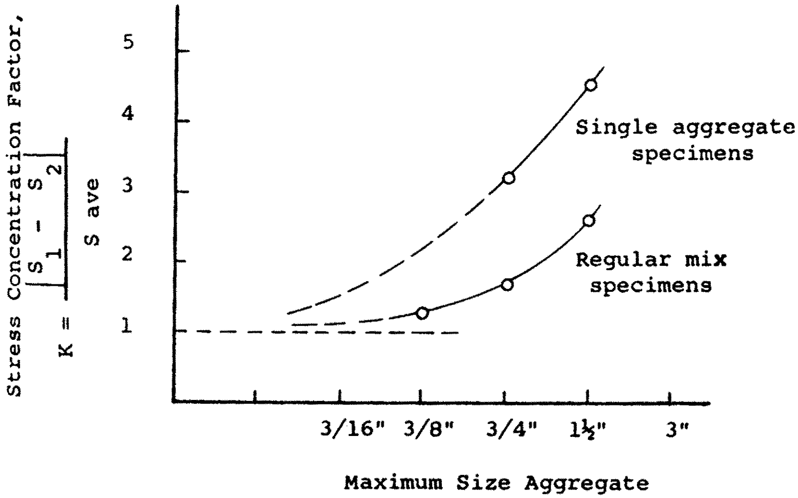


Figure 1. Change in stress concentration with variations in size aggregate in a cement paste matrix.

1. The highest fringe orders occur in the paste and most often are located along the edges of aggregates.
2. The central portion of the larger aggregates often have less than one fringe at specimen failure.
3. The isochromatic fringes, while tending to be a gradually increasing order of the same basic pattern, show that the maximum value of $S_1 - S_2$ changes from location to location as loading progresses. For example, the color pattern may indicate during the first part of loading that failure will occur at point 1, yet during the succeeding load interval the highest order will suddenly show at point 2, yet final failure occurs at point 3 which may not become obvious from the fringes until the last few hundred pounds of load.
4. Fracture of the thin specimens most often occurs in vertical planes both parallel and perpendicular to the coated face.
5. The progress of some few cracks could be followed by eye but pictures of them were difficult to obtain and fringe orders were so faded in their vicinity that values could not be obtained.
6. The inclusion of large aggregates in concrete increases local stresses and accelerates the fracture process.
7. Although cumbersome, the study of the behavior of the composite material concrete may be facilitated through the use of the principles of photoelasticity.