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Design and Mechanical Characterization of Fibre Optic Plate Sensor for Crack Monitoring

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The condition of many important concrete structures can be partially assessed through the detection and monitoring of cracking. Usually, crack detection in bridges is based on visual inspection. This procedure is time consuming, expensive, and unreliable; therefore, the use of cracking sensors is highly recommended. Nevertheless, most existing sensors/transducers are quite limited in their ability to detect and monitor cracks. This paper outlines the characteristics of fibre optic sensors for crack monitoring and a describes the improvements. The proposed technique does not require prior knowledge of crack locations, which is a significant benefit over existing crack monitoring techniques. Moreover, several cracks can be detected, located, and monitored with a single fibre. An ideal application of the sensor is in the monitoring of flexural cracks in bridges, which may appear at arbitrary locations along the deck, but are essentially perpendicular to the spanning direction. This report describes recent improvements introduced in the sensor to attain the necessary mechanical properties that enable the plate to crack together with the concrete, mainly by assuring that the plate has a brittle behaviour and breaks under a small strain. Consequently, the mechanical properties after the curing of polyester were evaluated considering different combinations of catalyst and accelerant. Bearing in mind the ductile behaviour of the polyester, different particles were added to change the sensitivity of the sensor. By changing the particle size distribution, the geometry (aspect ratio) and the density of the material added, it is possible to control the sensor's sensitivity, e.g., to obtain a sensor that detects thinner or wider cracks. For measuring and improving the adhesion of the sensor plate to concrete, a study of polyesters and epoxies as adhesives was conducted and pull-off tests were performed.

1. Introduction

Concrete structures degrade through the formation and propagation of cracks. Therefore, an effective method in determining the "health" of concrete structures is by crack detection and monitoring. Crack openings beyond 0.2 to 0.4 mm (depending on the

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environmental exposure) may lead to durability problems associated with steel reinforcement corrosion. Large openings beyond 1 to 2 mm, which may be caused by overloads during natural hazards, is a sign of severe damage and requires immediate action (such as temporary closing of a facility for detailed inspection and repair). Presently, crack monitoring is carried out with regular visual inspections, which is costly, time-consuming and not very reliable. A better approach is certainly in demand.

Recently, various researchers have developed fibre-optics-based crack sensors for concrete structures. Existing optical crack sensors are, however, limited in their application. For example, sensing based on fibre breakage[1] can distinguish between the presence and absence of cracking but cannot provide information on gradual structural degradation. Point sensors, based on the measurement of intensity loss due to deformation, developed by Ansari and Navalurkar,[2] can detect and monitor the opening of a crack only if the cracking occurs in a small region that is known a priori. In real structures where the crack location is not known, these sensors are not applicable.

Zako et al.[3] used an optical time-domain reflectometer (OTDR) to measure the cracking point by the Fresnel reflection of four optical fibres, which were bonded to the surface of a mortar beam with epoxy resin. In addition, crack propagation in the mortar beam was also monitored by the breaking sequence of four optical fibres. For this approach to work for a real structure, a very large number of fibres have to be incorporated, which may make the sensing scheme overly costly and impractical.

Gu et al.[4] developed a distributed fibre optic sensor consisting of individual segments spliced on one line. By measuring the Fresnel reflection at each splice between two pieces of fibre, the average strain within each piece can be obtained. Based on the strain reading, the severity of cracking within a certain region can be assessed. An OTDR was employed for the interrogation of the sensor signal. The structural monitoring capability of the sensor was evaluated through experiments with reinforced concrete beams. For accurate determination of crack location, the splices must be close. However, if the splices are placed very close to one another, costs will be high and the forward signal may drop markedly with distance (due to the presence of many reflection points), making the sensor inapplicable to real structures where a long sensing length is required.[5]

Cai et al.[6] applied distributed optical fibre sensing technology to detect the cracks in a small-scale plaster model of an arch dam. Using OTDR, the real time monitoring of cracks can be achieved. The use of this technology has shown that a sensor network bonded to the downstream surface of a dam does not affect the stiffness of the model, but the network must be correctly distributed.

Brown et al.[7] and Oka et al.[8] have applied Brillouin OTDRs for distributed strain sensing in concrete structures. By measuring the strain-induced frequency change in Brillouin backscattered light as a function of time, the strain distribution along a fibre can be derived. If a fibre is placed inside concrete, high local strain will be induced at a crack. In theory, the crack can hence be detected. In practice, however, the fibre may break owing to the high strain concentration, or debond to allow the "averaging" of the localized high strain over the debonded length. For cracks with relatively large openings, their presence is indicated by high values of averaged strain measured over a particular region of the specimen (Oka et al.[8]). However, since averaging removes the "peaks" in the strain

distribution, the number of cracks within the region and the corresponding crack opening cannot be determined. On the other hand, for cracks with small openings, it is questionable if the resulting small increase in averaged strain can reveal their presence. Hence, the method may not work for the detection of small cracks with 0.2–0.4 mm openings, which can facilitate water/salt penetration and steel corrosion.

A sensor for the reliable detection and monitoring of cracks in a concrete structure has recently been developed by Leung et al.[9,10] The sensor is based on the principle of distributed optical fibre microbending.[9] An optical fibre is embedded in the concrete element in a "zigzag" shape (Fig. 1). Using an OTDR, the light intensity distribution along the fibre is measured. Before the formation of cracks, the backscattered signal along the fibre follows a relatively smooth curve. In the straight portions of the fibre, the small loss is due to absorption and scattering. In the curved portion (where the fibre turns), macrobending loss may occur depending on the radius of curvature.

When a crack opens in the structure, a fibre intersecting the crack at an angle other than 90° has to bend to stay continuous. This perturbation in the fibre is very abrupt, and thus can be considered as microbending. This microbending results in a sharp drop in the optical signal. This intensity loss is detected and located by means of the OTDR equipment. From the magnitude of the drop, the crack opening can be obtained if a

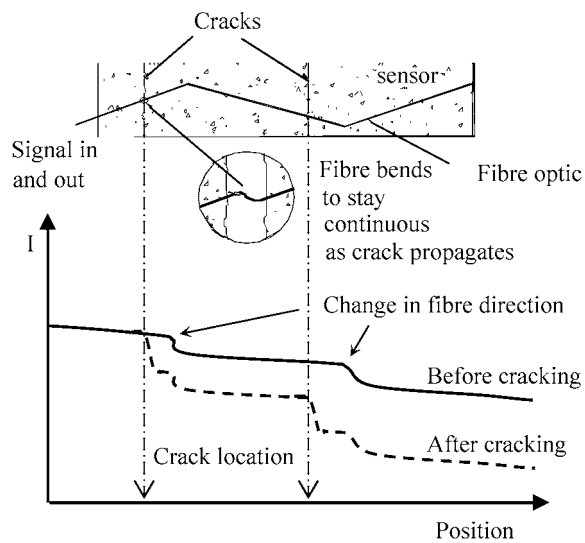

Fig. 1. Principle of operation of "zigzag" sensor.

calibration is available. Experimental results demonstrating the feasibility of multiple crack detection and monitoring with OTDR approach can be found in Leung et al.[10]

This technique does not require prior knowledge of the crack locations, which is a significant advancement over existing crack monitoring techniques. Moreover, several cracks can be detected, located, and monitored with a single fibre. However, the crack direction needs to be known. An ideal application of the sensor is in the monitoring of flexural cracks in bridges, which may appear at arbitrary locations along the deck but are essentially perpendicular to the spanning direction. A method for installing the sensor on existing structures has been recently proposed. It involves embedding the optical fibre into a polymeric plate to form a plate sensor,[9] which is then attached to the surface of the structure.

This paper reports recent improvements in the plate sensor to make it appropriate for use for the monitoring of cracks in bridges. This study was performed by researchers at the University of Minho in Portugal, and at the Hong Kong University of Science and Technology in China. Specifically, the work focused on the optimization of sensor plate properties. To achieve a reasonably fast but not overly exothermic curing procedure, the correct combination of catalyst and accelerant was selected; hence, the temperature of the peak exotherm and the time to peak exotherm temperature during the curing of polyester were evaluated.

The ductile behaviour of polyester observed in the tension tests can be useful for insuring that the sensor only detects cracks with a considerable width. On the other hand, to assure that the sensor detects thin cracks, it is important to assure that the plate is brittle. Thus, different particles were added to the polyester. The results of tension tests, carried out in specimens with different particle size distributions, geometries and densities of the materials added, demonstrate that it is possible to increase the sensitivity of the sensor effectively.

To guarantee the accurate behaviour of the sensor, it is important to establish a correct bonding procedure. Consequently, the bond between the plate and the concrete was evaluated through pull-off tests. In this work, the use of two adhesives, polyester and epoxy resin, was studied.

2. Sensing Principles

The plate sensor is a polymeric plate with an embedded optical fibre and works as a transducer. The principle is that once a crack forms in a structural element, the bonded polymeric plate will crack in the same location and direction as the crack.

Therefore, for the crack sensor to work properly, the bonding between the sensor and the concrete member has to be assured. If debonding occurs, the sensor plate will not be able to pick up the crack opening; likewise, the polymeric material implemented to build the transducer plate should have the necessary brittle mechanical behaviour to break right after cracking occurs in the concrete structure.

Moreover, the polymeric matrix of the transducer plate surrounding the optical fibre should allow a reliable sliding of the fibre when the crack is opening. In addition, to guarantee a similar boundary condition when microbending of the fibre occurs, similar

interfacial conditions between the matrix and the polymeric coating around the fibre should be assured; any imperfection of the matrix around the fibre could cause unequal light loss intensity for the same crack aperture.

There are many different design parameters that influence the sensor performance, such as the optical properties of the fibre and its inclination angle to the crack, as well as the mechanical properties of the fibre, polymeric coating and matrix. In view of the fact that it is desirable to detect small cracks (between 0.2 and 1.0 mm), the sensitivity needs to be sufficiently high. However, to detect many cracks, the sensitivity should not be too high. Otherwise, only a limited number of cracks could be detected since the dynamic range of any OTDR system is not unlimited. Therefore, to optimize the design of the crack sensor, an understanding of the optical and mechanical behaviour of the sensor is required.

Recently, crack simulating specimens, which are 2"×2"×3/8" epoxy blocks with an optical fibre placed inside a hole (254 μm diameter) at different angles (30º and 45º), were used to perform controlled experimental tests[5] to simulate the power loss of the sensor during the opening of a crack.

The objective of this investigation is to identify a suitable polymeric material from which to make the sensor plate. The specific requirements include (i) the curing procedure for the polymeric resin should be reasonably fast but not overly exothermic, (ii) the hardened polymeric plate should be brittle and break under a small strain, and (iii) the polymeric plate should achieve a good bond with the concrete. The first requirement is related to the ease of sensor fabrication. Experiments can be performed with the incorporation of different volumes of accelerant and catalyst, to identify the correct polymer composition. The second and third requirements need to be satisfied for the proper performance of the sensor; namely, the plate should crack together with the concrete member.

The failure behaviour of the polymeric plate can be controlled by the incorporation of fine particles (granite, calcareous, metakaolin, quartz, river sand, and abrasives) and measured with a direct tensile test. The bond between the plate and the concrete can be evaluated through a pull-off test. In the following sections, these investigations are described in detail.

3. Thermal and Mechanical Properties of Polyester

The mechanical properties of cured polyesters are defined by the peak exotherm temperature and the time to the peak exotherm temperature during the cross-linking reaction that consolidates the unsaturated polyester resins (UPR) in an infusible and rigid material. Once the radical formation is initiated by a suitable catalyst and subsequent polymerization, the heat activates the cross-linking reaction, which starts to thicken the UPR, in competition with a viscosity reduction and a softening of the solid resin. Finally, when the peak exotherm temperature is achieved, the result is a rigid cured polymer.

Several compositions were tested to build the polymeric plate using different combinations of Butanox M50 catalyst and an accelerant (cobalt salts diluted to 10%) with a non-saturated resin of polyester with an isoftalic acid-base mean reactivity (Resipal VUP 4686/62). To assess the curing behaviour, cure tests based on the recommendations of the

Society of Plastic Engineers (SPE cure test[11]) were performed, which rely on following the cure reaction temperature in relation to time and calculating three components: the initiation (gel) time, the peak exotherm temperature, and the time to peak exotherm temperature. Figure 2 shows the cure reaction temperature related to time for three different combinations of accelerant and catalyst in 20 cm^3 specimens of polyester resin.

The results of the cure test demonstrate that small volumes of catalyst generally cannot assure the curing of UPR at ambient temperature. The radical formation that is necessary to start the polymerization reaction is slow at ambient temperature. To speed up the radical formation in a controllable way, the volume of catalyst must be increased. Moreover, an accelerator premixed with UPR plus a suitable portion of catalyst promotes not only the polymerization reaction in UPR but also the reaction of organic peroxides, increasing the peak exotherm temperature. However, the presence of large volumes of accelerant in UPR with a suitable portion of catalyst can be overly exothermic. If the resins are poured without temperature control, the unacceptable levels of heat from the exotherm could result in resin shrinkage and possible cracking. As a general recommendation, the volume of poured resin should be a function of surface area and ambient temperature. For a large volume with a small surface area, the catalyst plus accelerant amount must be reduced significantly, relative to the amount used when the same volume of resin is spread over a much larger surface area. Additionally, pouring in cooler conditions requires more catalyst plus accelerant than in warmer ambient temperature conditions.

To develop a curing procedure that is reasonably fast but not overly exothermic, combinations based on catalyst at 2.5% and accelerant at 0.5% were selected to prepare specimens for mechanical testing. As seen in Fig. 2, the corresponding initiation time is close to 16 min, and the peak exotherm and the time to peak exotherm temperature are 165°C and 19 min, respectively. As illustrated in Table 1, five different combinations of catalyst and accelerant have been tested to produce the polyester.

To gather the necessary parameters and to characterize the mechanical behaviour of the polymeric transducer plate, several tension tests were carried out using a servo-controlled test machine (Instron series 4505, Fig. 3), following the recommendations of ISO 527-1.[12] The influence of the environmental temperature on variations in tensile properties was analyzed.

Figures 4–6 show the tensile properties of the five polyesters studied and the epoxy resin (Sikadur® 32N) used as adhesive in the pull-off test. These figures were compiled from the results obtained from 96 tests (6 per material). In these figures, ¢ is the maximum value, is the mean value, " is the minimum value, and represents the ± standard deviation. These results show that the tensile properties of the polyester are different for different combinations and become significant at 40°C. This is a direct result of the peak exotherm and the time to peak exotherm temperature reached during the polymerization of UPR, which is conditioned by the amount of catalyst and accelerant.[13]

The results demonstrate that the curing of UPR and its final mechanical properties can be controlled by the variables 1) the percentage of catalyst plus accelerant, and 2) the ratio of accelerant to catalyst, with a reduction in stiffness and resistance to tension when a low peak exotherm and a long time to peak temperature, respectively, occur.

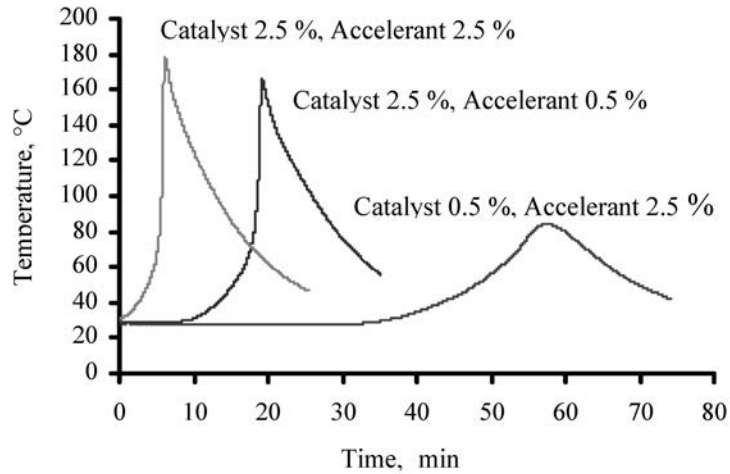

Fig. 2. Cure reaction temperature related to time obtained for different combinations of accelerant and catalyst in 20 cm^3 specimens of polyester resin.

Table 1
Combinations of catalyst and accelerant tested.

Material	Catalyst (%)	Accelerant (%)
Pol. 1	2.50	1.50
Pol. 2	2.50	0.50
Pol. 3	2.50	0.05
Pol. 4	1.67	0.33
Pol. 5	1.50	0.50

Fig. 3. Tension tests of polymeric materials.

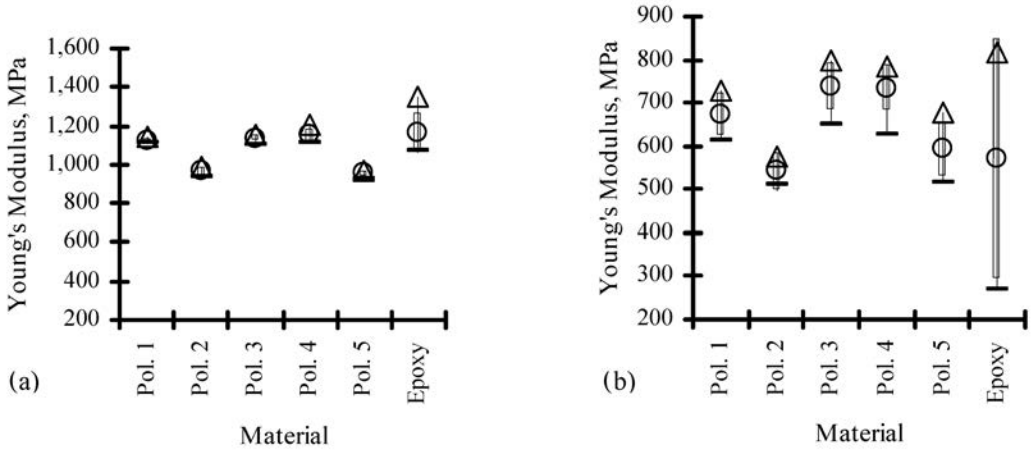

Fig. 4. Young's modulus determined at (a) 20 and (b) 40°C.

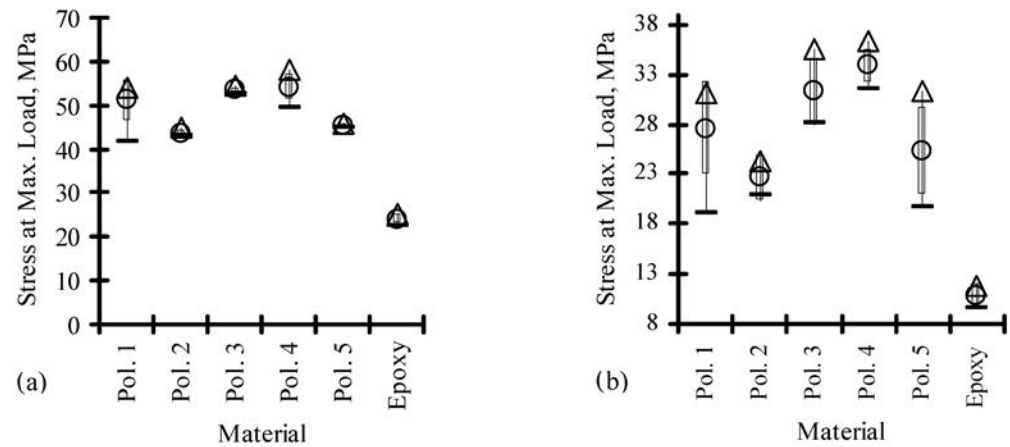

Fig. 5. Stress at maximum load determined at (a) 20 and (b) 40°C.

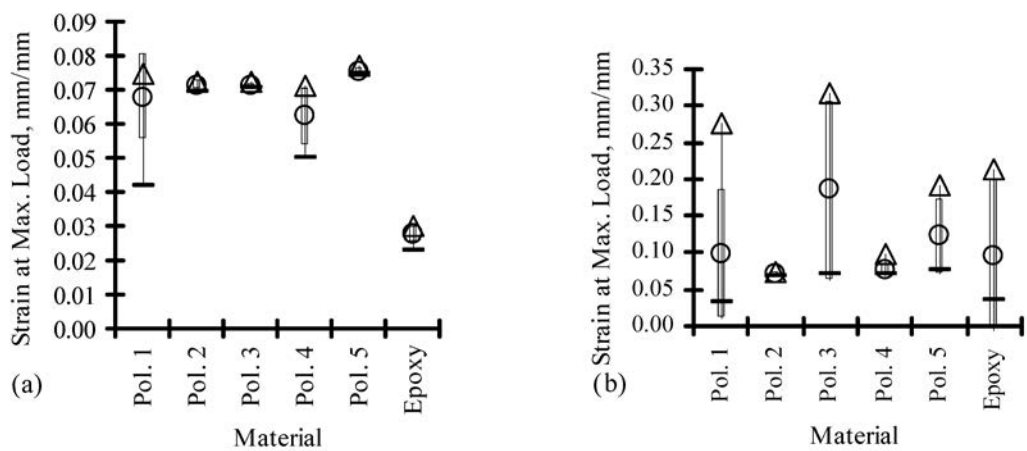

Fig. 6. Strain at maximum load determined at (a) 20 and (b) 40°C.

The polyesters Pol. 1 to Pol. 5 do not exhibit any brittle mechanical behaviour; on the contrary, these materials showed high strain capacity at failure. Pol. 2 is the combination with the lowest resistance to tension. One significant change occurred when an accelerant based on a salt of cobalt diluted to 1% with styrene monomer was employed, which gave rise to the material referred to as Pol. 2a1. Material failure occurs immediately after the peak load, which is reached with a minimal sign of elongation. Therefore, polyester Pol. 2a1 was selected as the main component to produce the sensor plate. Figure 7 shows the stress-strain curve for tension for Pol. 2a1, compared with the original Pol. 2 and epoxy.

4. Mechanical Properties of Modified Polymeric Materials

In thermosetting plastic materials, it is relatively common to compound the partly reacted resins (prepolymers) with a variety of fillers and reinforcements to achieve improved mechanical properties in the finished product after the cross-linking reaction has been completed during the moulding process.[11] The amounts of filler incorporated in the moulding compound can be very substantial, and often well in excess of the amount of resin, with the main purpose being to reduce the cost.

To further reduce the cracking strain of the polyester Pol. 2a1, fine particles were employed as additives to the polymer. In this study, the use of the following additives was tested: four fillers (granite, calcareous, metakaolin, and quartz), two river sands classified

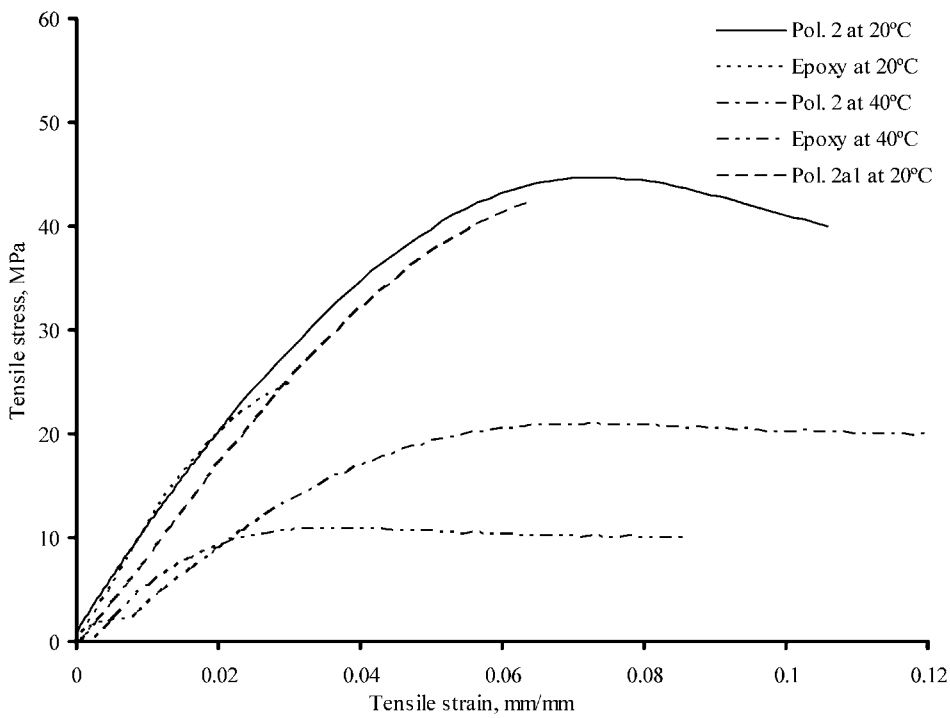

Fig. 7. Example of typical σ-ε curves resulting from uniaxial tensile tests.

by the size of the particles as 200 (0.08 mm) and 80 (0.16 mm), and two abrasives commonly used to determine the resistance to surface abrasion, referred to as a A1200 and A600. The epoxy (Sikadur® 32N) was also studied to evaluate whether it can be used as a material for the transducer plate. In the following figures, it is referred to as epoxy, and the results for Pol. 2a1 and Pol. 2 are presented.

To identify the relationships between the mechanical properties of the final product and the material used as an additive, changes in the mechanical properties were studied in terms of particle size and the density volume of the material added (DVMA).

Figures 8–10 show the results of 132 tests (6 per material). The amounts of the additives tested correspond to approximately 10% (Figs. 8(a)–10(a)) and 20% (Figs. 8(b)–10(b)) in density volume. Table 2 gives a summary of the results in comparison to Pol. 2a1. The increment in Young's modulus and respective reductions in the stress and strain values at maximum load are listed. Pol. 2a1 has a Young's modulus of 813 MPa, with a stress and strain at a maximum load of 41 MPa and 0.07 mm/mm, respectively. In comparison to Pol. 2a1, the epoxy exhibits a mean increment in Young's modulus of 43% and a mean reduction of stress and strain of 41 and 59%, respectively. In the case of the river sand, the particle size had a significant effect on the mechanical behaviour. The material becomes more rigid and less resistant to tension. When the particle size is changed to higher values, the overall effect is minimized when the DVMA is increased, as the polymeric resin approaches its packing limit. Figure 11 shows the stress-strain curve of the material with least tensile stress and strain at maximum load (river sand particle size of 0.16 mm). This material exhibits a mean Young's modulus of 1865 MPa with a mean stress and strain at maximum load of 18 MPa and 0.01 mm/mm, respectively.

The mechanical behaviour of compounds with filler is determined by the particle size distribution, geometry (aspect ratio), and density of the filler. In contrast to river sand, the effect of an increment in the DVMA is significant: both abrasives and quartz report high increments in stiffness while the other fillers present a reduction in the resistance to tension. Nevertheless, with the exception of metakaolin and abrasive A1200 added to Pol. 2a1, all compounds exhibit ductility after the elastic region.

To make the sensor plate, a filler of abrasive A1200 at 20% in density volume was proposed as an additive. Together with Pol. 2a1, the particulate composite exhibits a mean Young's modulus of 1858 MPa with a mean stress and strain at maximum load of 26 MPa and 0.015 mm/mm, respectively. This provides a rigid and brittle material that breaks under a small strain, adheres well to concrete, and cracks in the same location and direction as the crack. Figure 11 shows the stress-strain curve under tension of pure Pol. 2a1, compared with Pol.2a1 with fillers of metakaolin, and abrasive A1200. The differences in the change in mechanical properties among these fillers are basically the stiffness and the resistance to tension. Although the compound of metakaolin has a reduced resistance to tension, it is not recommended because it exhibits no dimensionally stable change during and after moulding.

The choice of polyester for making the sensor plate is primarily because of it high performance and competitive price. The technique currently implemented for volume production allows for the sensor to be made precisely as specified off-site. The polyester is durable and able to withstand environmental attacks that could include chemical attack

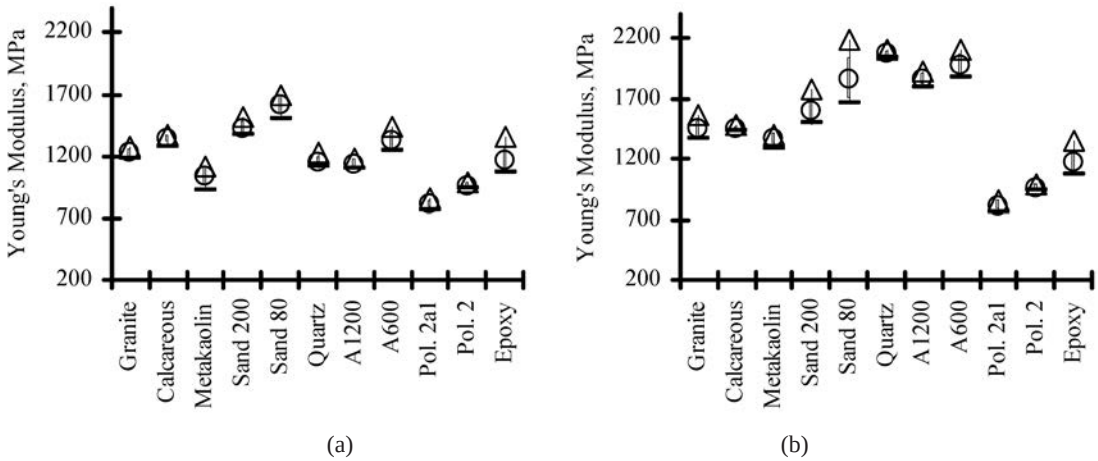

Fig. 8. Young's modulus at 20°C of Pol. 2a1 with different additions: (a) 10% of added material; (b) 20% of added material.

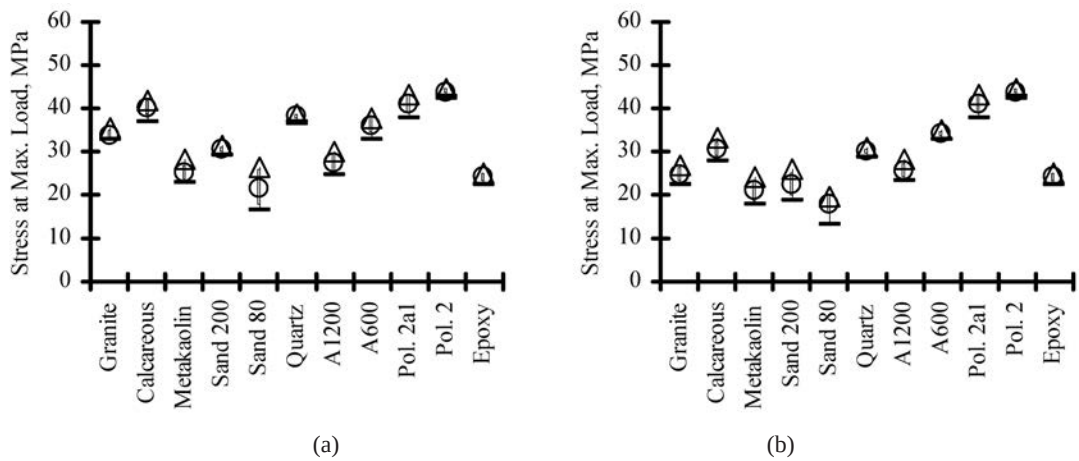

Fig. 9. Tensile stress at maximum load at 20°C of Pol. 2a1 with different additions: (a) 10% of added material; (b) 20% of added material.

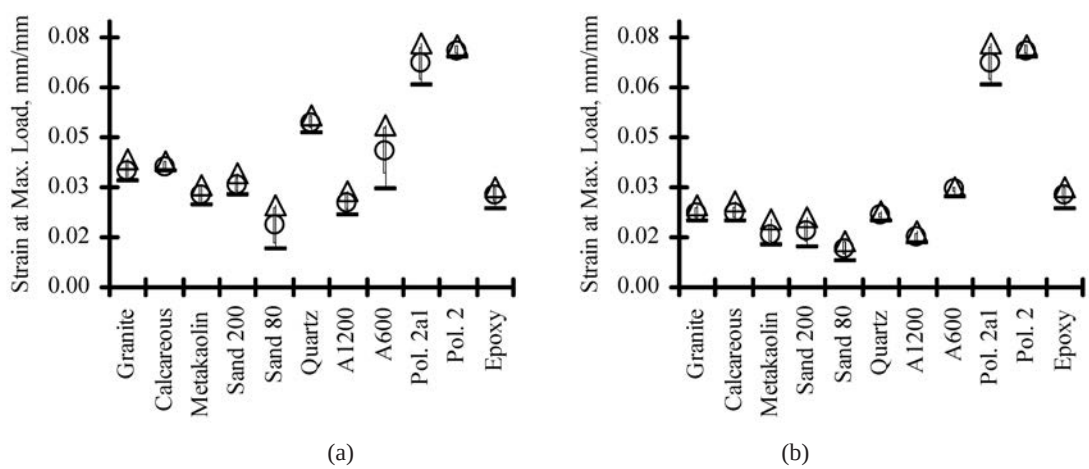

Fig. 10. Tensile strain at maximum load at 20°C of Pol. 2a1 with different additions: (a) 10% of addition material, (b) 20% of addition material.

Table 2
Mean comparison with Pol. 2a1. Values in percentage of increment of Young's modulus, E_t, and reduction of stress and strain at maximum load, σ_t and ε_t.

Material	Density, ρ (g/cm^3)	10% of DVMA			20% of DVMA		
		E_t	σ_t	ε_t	E_t	σ_t	ε_t
Granite	2.67	50	17	48	77	40	67
Calcareous	2.76	64	2	46	79	26	67
Metakaolin	2.57	27	39	59	68	49	76
Sand 200	2.71	75	26	54	96	46	75
Sand 80	2.71	98	48	73	129	57	83
Quartz	2.66	42	7	26	154	27	68
A1200	3.02	40	33	62	128	38	78
A600	3.21	63	12	39	144	17	57
Mean	2.79	57	23	51	109	38	71
Maximum	3.21	98	48	73	154	57	83

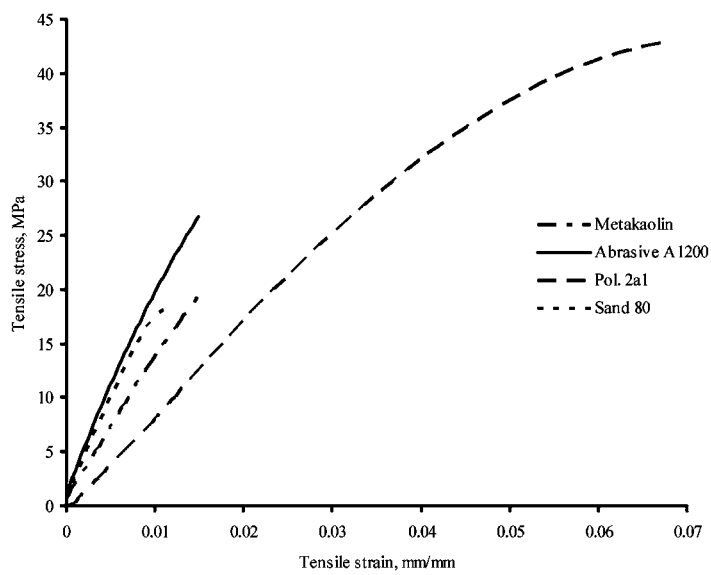

Fig. 11. Stress-strain relation under tension at 20°C of Pol. 2a1 with river sand 80, metakaolin, and abrasive A1200 added.

from pollution, severe cold and ice, or desert heat. The durability of polyester has indeed been tested over many years in harsh marine environments, such as the conditions faced by a bridge over a waterway.

5. Experimental Analysis of Bond Properties

The establishment of a strong bond of the plate to the concrete surface is an important prerequisite for the successful performance of the sensor. For a successful bonding application, the strength of the substrate surface is equally as important as a clean and dry surface, the absence of contaminants, and the best profile that can be achieved. Surface blasting with hand-held mechanical equipment was used to attain a uniform surface texture and to remove the laitance (the weak alkaline surface residue), dirt, and dust until coarse aggregates are exposed. Any oil and/or grease contamination on the concrete must also be removed prior to bonding. Cleaning concrete with steam is an effective means of removing heavy deposits of oils and greases. It consists of cleaning the surface with a jet of high-pressure steam sufficient to remove contaminants. The importance of cutting back the concrete to a clean sound surface cannot be overemphasized, since adhesion relies partly on the mechanical interlock by the penetration of the surface pores, and partly on the physical forces of attraction to clean, high energy aggregate surfaces.[14] Moreover, to have better compatibility with the adhesive surface pretreatment of the sensor plate is recommended. An effective pretreatment of the plate includes a fine blasting with sand paper and cleaning with pure acetone (C_3H_6O), to remove any contaminants such as oils, dirt, and release agents.

To investigate the global bonding behaviour of the sensor plate empirically, initially a modified three-point bending test was carried out over three beams of plain concrete of low resistance (Fig. 12). To obtain a localized crack opening mid-span in all tests, a notch of 200×3 mm was introduced mid-span on each side of the beam. The material of the plate was Pol. 2, and the adhesives correspond to Pol. 2, Pol. 3, and Pol. 5 (Table 1). As can be observed in Fig. 13, the bonding between the sensor and the concrete was properly assured when Pol. 2 was used as an adhesive, and the cracks in the plate and beam seem to occur at the same location. Nevertheless, because the results for Pol.2 and Pol.5 show a peeling of the sensor plate caused by weak bonding and/or mechanical properties of the plate, the adhesion was measured and improved.

A number of tests exist for measuring adhesion in the laboratory. In this study, pull-off tests were used. To simulate the bonding condition for the sensor plate to the concrete, the pull-off test (Fig. 14) involves, first, the rectification of a bronze disc glued to a small part of the sensor plate. Then, the disc and polyester plate are bonded to a partial core of concrete drilled perpendicularly to the surface. The disc is pulled off by direct tension using a hydraulic precision instrument at a controlled loading rate (1 MPa/s).[15] The peak force in kN is recorded and transformed to adhesion/tensile strength by dividing by the core area. To compare an adhesive material which spreads and adheres well to the substrate to one which, when cured, yields a highly cross-linked structure possessing significant cohesive strength in a short time, two epoxies (MBrace Resin 55 and Sikadur® 32N) and

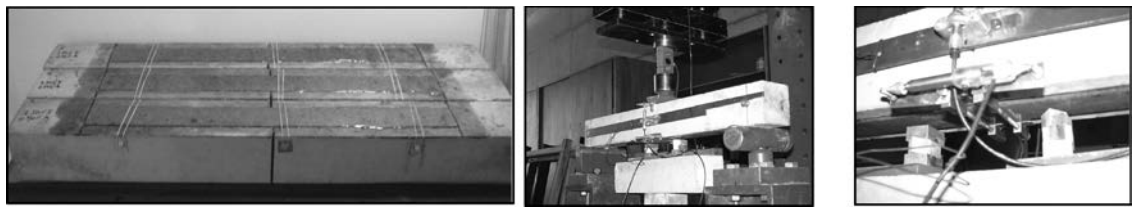

Fig. 12. Modified three-point bending tests.

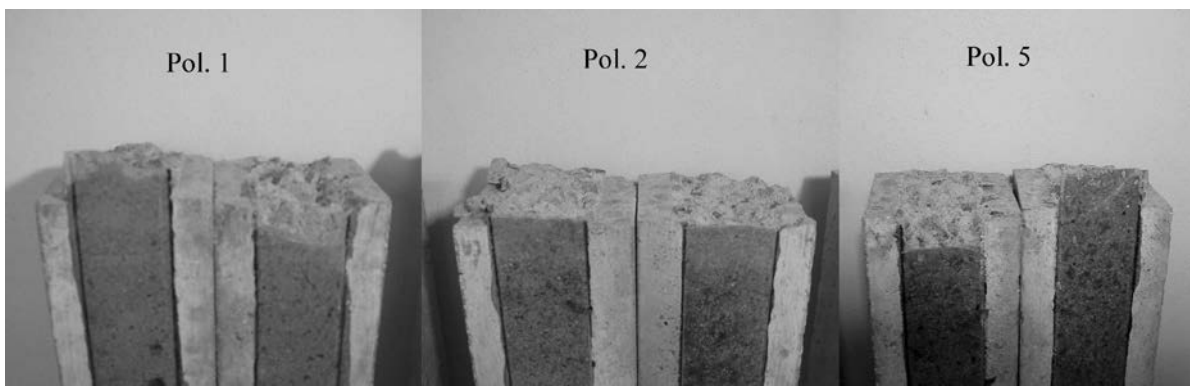

Fig. 13. Specimens after failure.

two polyesters (Pol. 2, and Pol. 2a1) were studied as adhesives between the polyester and the concrete.

Figure 15 illustrates the results of the 72 pull-off tests carried out in a fixed-alignment adhesion tester (DYNA, T. F. 16 kN, Fig. 16). In this figure, S_u is the pull-off stress, reached at maximum load, of three different concretes (C1, C3, and C5). The mean compression resistance of these concretes is C1 ≈ 28 MPa, C2 ≈ 59 MPa, and C3 ≈ 63 MPa. Theoretically, the tensile strength corresponds to the applied stress when cohesive failure occurs in the concrete. In the course of tests when epoxies were used, cohesive failure was always observed. The results showed that the polyester resins, in spite of being more resistant to tension compared to epoxies, do not achieve sufficient mechanical interlock by penetration into the concrete. Pol. 2a1 has a longer curing time compared to Pol. 2, and consequently has more time for impregnation to enhance the adhesion. The epoxies with long curing times (24 h) facilitate the flow of the material over the concrete surface

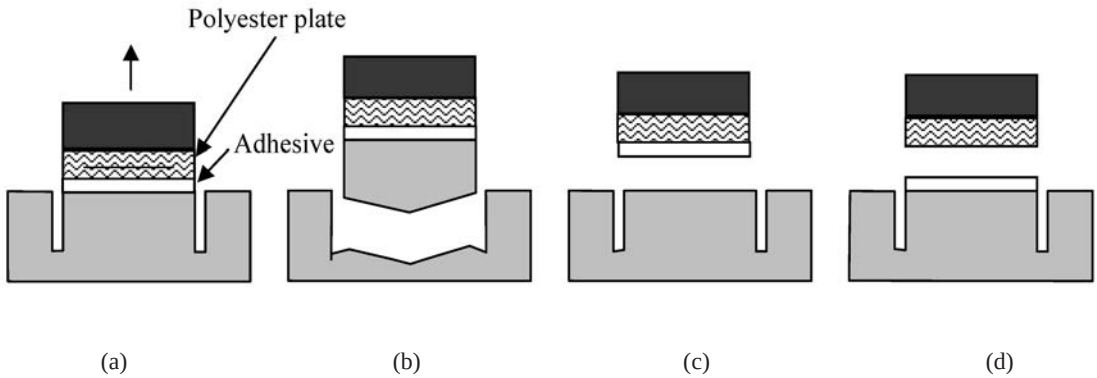

Fig. 14. Failure modes in pull-off test: (a) pull-off test, (b) cohesive failure in concrete, (c) adhesive failure at adhesive/concrete interface and (d) adhesive failure at polymer/adhesive interface.

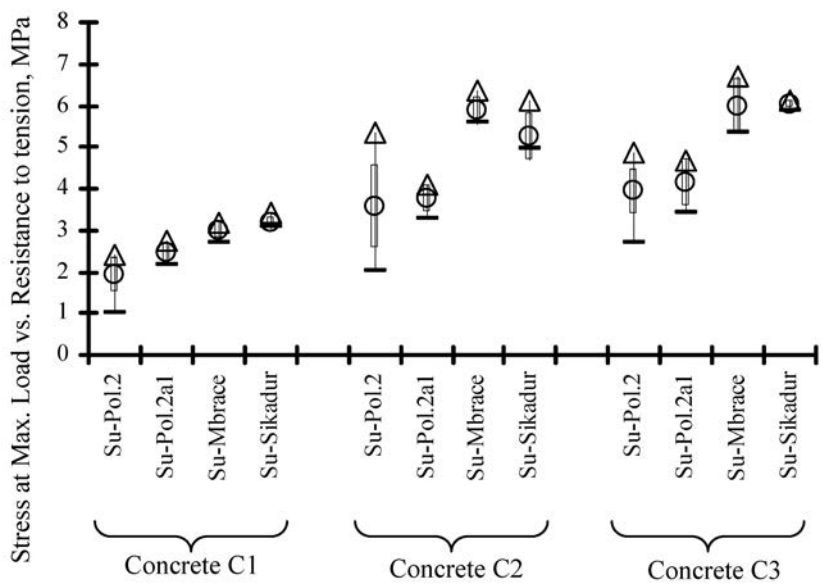

Fig. 15. Pull-off stress of adhesion/tensile strength.

together with increased molecular mobility; which enhances the wetting potential. For MBrace Resin 55, failure occurs along the resin/plate interface in a number of tests. For future implementation of the sensor, the epoxy Sikadur® 32N is proposed as the adhesive, as it makes a strong bond with polyester plate.

Fig. 16. DYNA, T. F. 16 kN, specimen preparation and rectification in pull-off tests.

6. Conclusions

In this paper, an overview of the characteristics of fibre optic sensors for crack monitoring and descriptions of the improvements is presented. The challenges in developing the new sensor to attain the necessary mechanical properties for crack sensing to be feasible in practice were explained and discussed.

The tensile properties of the polyester present significant variations. This is a direct result of the peak exotherm temperature and the time to peak exotherm reached during the polymerization of the liquid resin, conditioned by the amounts of catalyst and accelerant. The results demonstrate that the peak exotherm temperature and the time to peak exotherm can be controlled by two variables: the percentage of catalyst plus accelerant, and the ratio of accelerant to catalyst. Nevertheless, with the best combination, the polymeric material does not exhibit brittle mechanical behaviour. On the contrary, it is too ductile and does not crack together with the concrete. Particles of different sizes and DVMAs were therefore added to change the sensitivity of the sensor. With the modified polymeric materials, results of tensile tests proved that a brittle mechanical behaviour can be achieved. According to the test results, it is recommended that the sensor plate be made with Pol. 2a1, with the incorporation of abrasive A1200 at 20% in density volume. This produces a rigid and brittle material that breaks under small strain, adheres well to concrete, and cracks in the same location and direction as a crack in concrete.

In this work, a bonding procedure involving the pretreatment of a sensor plate for a strong bond to the concrete surface was established. To study the global bonding behaviour of the sensor plate empirically, modified three-point bending tests were performed. The results demonstrate that the brittle mechanical behaviour of the sensor plate is essential; the risk arises that the plate will debond from the concrete surface. Moreover, after a comparison of the results, a prolonged curing time of the adhesive seems to be an important factor that governs the penetration of the adhesive into concrete to provide sufficient mechanical interlock.

To measure and improve the adhesion of the sensor plate to the concrete, pull-off tests were performed. To compare adhesives with short and prolonged curing times (more and

less resistant to tension), a study of polyesters and epoxies as adhesives was carried out. The results indicate a relatively large scatter and low adhesion/tensile strength when polyesters were used; in contrast, the pull-off stress is theoretically the same as the tension resistance of the concrete when epoxies were implemented as adhesives (where failure almost always occurred in the concrete). Based on our tests, the best interface compatibility with the sensor plate was attained with the epoxy Sikadur® 32N.

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