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High sensitivity and resolution sensor plastic optical fiber for determining compressive and tensile tensor concrete applications

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High sensitivity and resolution sensor plastic optical fiber for determining compressive and tensile tensor concrete applications

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Abstract. This research discusses sensors based on plastic optical fiber (POF) for concrete compressive tests and concrete tensile tests. Sensors are made of plastic optical fibers without coat attached to concrete surfaces or planted in concrete with straight, one bending, and two bending configurations. Sensors are attached to concrete with four configurations to find the best sensitivity and resolution values. The pressure on the sensor is related to the loss of power. The best sensor characteristic based on plastic optical fiber for concrete compressive test and the concrete tensile test is the sensor with two bending configurations that are planted in concrete. The sensitivity and resolution values in the concrete compressive strength test were 0.085 volts/kN and 0.047 kN. While the value of sensitivity and resolution of the concrete tensile test obtained is 0.082 volts/kN, and 0.048 kN. Sensor-based on plastic optical fiber has the advantage that is low cost and simple in measurement method that can be applied for monitoring the condition of the building structure.

1. Introduction

The increasing need for building construction requires the availability of materials such as concrete. Concrete is one of the main components used in civil engineering applications such as roads, buildings, dams etc. The concrete structure generally consists of a mixture of the cement, the coarse and fine aggregate, water, the air, and another chemical mixing. The cement acts as a matrix binding aggregate that reaches its power as a result of the hydration process. The mixture of aggregates and mortar subsequent processing directly affects the structural properties which produced from the concrete. The high compressive strength can be achieved in concrete structures; concrete is known to occur early damage due to continuous exposure to the environment. Monitoring is required before any damage occurs to the concrete. If it is left untreated, it may result in damage to the concrete. Forms of damage to the concrete include the occurrence of cracks, broken, and also destroyed. Several methods of monitoring the concrete structure using a sensor system that has been developed, one of which is used optical fiber that can be applied as a multipurpose sensor [1-3].

The optical fiber as a sensor has many advantages over other types of conventional sensors such as high sensitivity, fast response, resistance to electromagnetic interference, corrosion, supple, and easily connected to computers with advantages such as small size, lightweight, resistant to high voltage, and capable of making long-distance measurements. Sensors that use optical fibers can cope with the weaknesses for electronic sensors [4-9]. Based on the material, an optical fiber is divided into two types that glass optical fiber (GOF) and plastic optical fiber (POF). Plastic optical fibers are mostly used as sensors because they are more flexible than glass optical fibers and are not easily damaged [4,10-12].

Sensor-based on POF have been developed to detect cracks in concrete [1]. Besides, plastic optical fibers can measure several other parameters, such as strain, flexibility, and shift [2,13]. The plastic optical fiber sensor can be applied and developed in the world of civil engineerings, such as concrete bending tests and crack detection [14-17]. It can be the basis of sensor development to detect other physical parameters in the civil engineering world. Therefore, this research designs and manufactures sensors based on plastic optical fiber for compression test and concrete tensile test. Sensors made have the advantage of having simplicity in the measurement system, easy fabrication with low cost and data acquisition done by microcontroller Arduino then the results are displayed on the computer.

2. Experimental Setup

The sensors are made of uncoated POF with lengths adapted to cylindrical test concrete with a diameter of 10 cm and a height of 20 cm. Sensors are made with a variety of straight or curved configurations that are embedded and planted in concrete. The main tool and matter are the Light Emitting Diode (LED), phototransistor, and POF. Types of plastic optical fibers used as sensors have the diameter of coat, cladding, and core 2.2 mm, 1 mm, and 0.98 mm respectively. The core of the plastic optical fiber is made of *polymethyl methacrylate* (PMMA) material. For the core and cladding refractive index are 1.492 and 1.402, respectively, with a numerical aperture (NA) is 0.5.

The primary principle in this research is the design and manufacture of compressive and tensile tensor using POF without a coat. The sensor attached and planted in the concrete. Each end of the plastic optical fiber is connected with LED as the light source and phototransistor as a detector. The increasing of the load had been given can implicate compression and tensile on the optical fiber embedded and planted in the concrete. The compression and tensile causes the light from LED that propagates in the optical fiber decreases that detected and received by the phototransistor. The output from the phototransistor amplified using the differential amplifier. Then, the output converted by the microcontroller Arduino and displayed on a computer in the form is the output voltage. Schematic diagram of the compression and concrete tensile testing sensor illustrated in Figure 1.

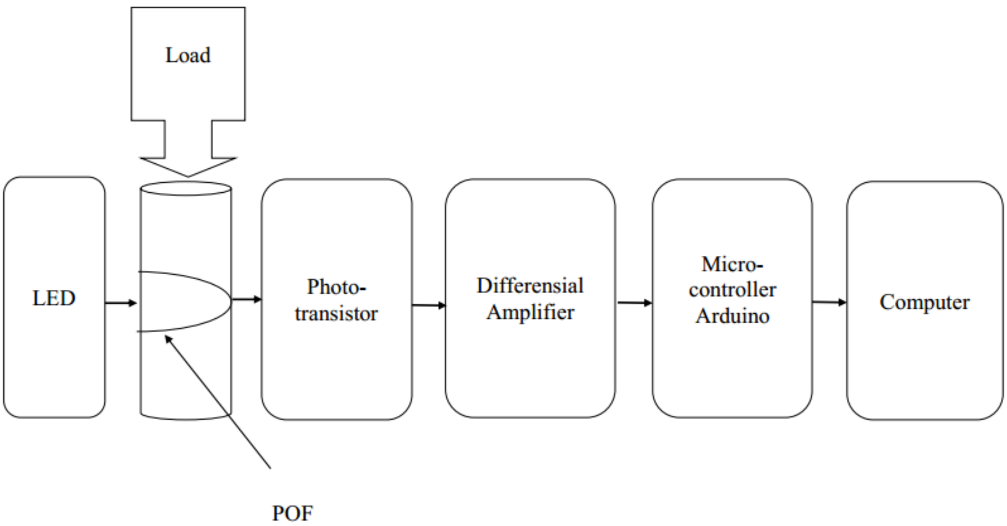

Figure 1. Schematic diagram of the compression test sensor and concrete tensile based on POF.

The configuration of the sensor using plastic optical fiber for a concrete compressive test, as shown in Figure 2. The design of the sensor has been made with two variations of sensor installation that is taped to a concrete surface or planted in concrete. For taped to a concrete surface use straight configuration. For the variation of POF that planted on concrete use, three types of configuration are straight, one bending, and two bendings planted in the concrete. The configuration of the sensor is based on plastic optical fiber for a concrete tensile with four types variation, i.e., straight taped to the concrete, straight planted in concrete, one bending planted in concrete and two bending planted in the concrete test are shown in Figure 3.

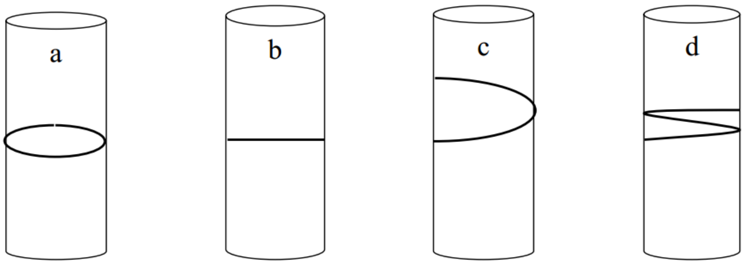

Figure 2. The configuration of the sensor based on POF for a concrete compressive test.

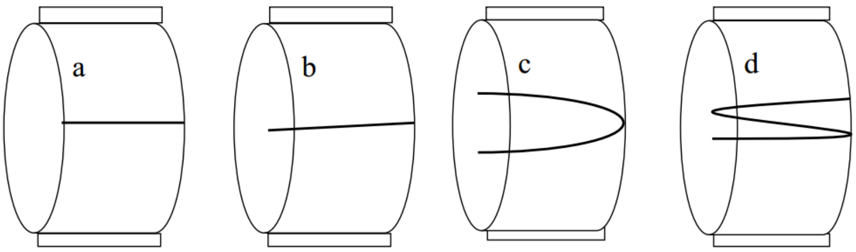

Figure 3. The configuration of the sensor based on POF for a concrete tensile test.

Furthermore, in Figure 2 the POF's length for straight configuration taped in a surface, straight planted, one bending planted, and two bendings planted in concrete are 35 cm, 15 cm, 30 cm, and 45 cm respectively. Likewise, in Figure 3 the POF's length for straight configuration taped in a surface, straight planted, one bending planted, and two bending planted in concrete respectively 15 cm, 25 cm, 50 cm, and 75 cm. The concrete testing tool uses a Universal Testing Machine (UTM) that has the smallest scale value for measuring instrument is 0.01 kN. The UTM provides loads and stops automatically until the concrete is no longer able to accept the load. This tool can provide loads that change slowly, medium, or fast with a maximum load of 1000 kN. The length of the test time is proportional to the accretion of each sample of concrete. The sensor measurement process aims to determine the best characteristics of the sensor that has been made by giving a load.

3. Results and discussions

The experimental setup has been prepared to measure and monitoring compressive strength testing and tensile strength of concrete. A sensor-based on POF without a coat used with two variations of sensor installation that is taped to a concrete surface and planted in concrete. Sensors attached to concrete surfaces with circular configuration forms in concrete compressive test and straight configuration in a concrete tensile test. Furthermore, the sensors are planted in concrete with three configurations that straight, one indentation, and two indentations. The output voltage measurement results from the four sensor configurations can be calculated and compared value of range, sensitivity, and resolution, respectively.

The data from sensor testing results is analysable by calculating the sensitivity and resolution value, respectively. This result to determine the best characteristics of the sensor has been made. The sensitivity shows the sensitivity of the sensor to the measured quantity. The sensor sensitivity can obtain by dividing the difference in the output voltage and the different of forces applied to the concrete. The equation of the sensitivity written in equation 1 [6-7,15,17]:

$$S = \frac{V_{max} - V_{min}}{F_{max} - F_{min}} \quad (1)$$

with, V_{max} and V_{min} are the maximum and minimum output voltage displayed on the computer. F_{max} is the maximum load and F_{min} is the minimum load read on the UTM.

Resolution is the smallest amount of value that can be measured by the sensor. The sensor resolution can be formulated as follows in equation 2 [6-7,15,17]:

$$R = \frac{N}{S} \quad (2)$$

with N is the smallest value that can be measured of 0.004 V and S is the sensitivity value of the sensor.

The value of compressive strength on concrete using a sensor based on POF for the concrete compressive test can be formulated as follows:

$$P = \frac{4F_{max}}{\pi D^2} \quad (3)$$

With F_{max} is the maximum load and D is the diameter of the concrete.

The value of concrete tensile strength on sensor-based on POF for the concrete tensile test can be formulated as follows:

$$P = \frac{2F_{max}}{\pi DL} \quad (4)$$

with F_{max} is the maximum load, D is the diameter of the concrete and L is the length of the concrete.

3.1 Sensor-based on POF for concrete compressive test

Measurement was made using various sensor installation for concrete compressive testing, i.e., straight taped, straight planted, one bending planted and two bends planted in concrete. The measurement results are read on the computer as an output voltage and proportional to the load had been given by the UTM. The response to the addition of load to changes in output voltage based on POF for the concrete compressive test is shown in Figure 4.

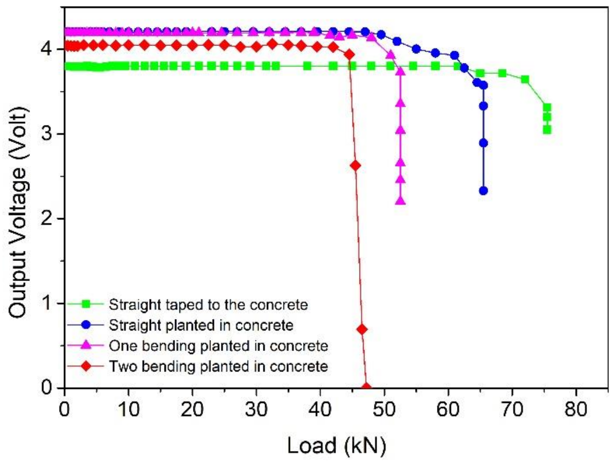

Figure 4. The response of the output voltage changes to the load changes for the concrete compressive test.

Figure 4 shows that the change of output voltage to the load changes is applied to a sensor based on POF with various configurations. The load and each configuration obtained a different response. When the concrete is given pressure indicates the increase of load. The increase of load causes the force to increase and implicate strain on the optical fiber or change in length and experiences both large and small indentations. The change is then causing loss of powers in the POF. The amount of power losses in the optical fiber sensor causes decreasing of the light intensity received by the phototransistor and output voltage to decrease.

In Figure 4, the output voltage for each measurement decreases significantly. It indicates the critical point of each measurement, and concrete begins to crack. The addition of the load causes the force and pressure on the concrete to increase so that the concrete begins to crack at the maximum load limit. Each sensor installed on the concrete has a different maximum load. Similarly, the compressive strength of the concrete decreases proportionally to changing the sensor configuration. The highest compressive strength is obtained in the sensor configurations taped to the surface of the concrete with maximum loads of 75.5 kN. While the lowest compressive strength is on the sensor configuration with two bending and load value of 47.2 kN. In figure 4, the drop values because bends and longer the length of the sensor that is embedded or planted in the concrete will reduce the compressive strength of the concrete have been tested. However, the sensitivity and resolution of the sensor get better. Besides, the more POF sensors embedded in the concrete greatly affect the compressive strength of the concrete, and the more POF that are embedded in the concrete, the lower the compressive strength concrete.

3.2 Sensor-based on POF for concrete tensile test

The setup experiments have been prepared to measure and monitor the response of concrete tensile testing, i.e., straight taped, straight planted, one bending planted and two bending planted in concrete. The measurement process also using UTM that the load is given proportional to the output voltage. The result is then displayed on the computer with the form output voltage. The measurement result and response for the concrete tensile test are shown in Figure 5.

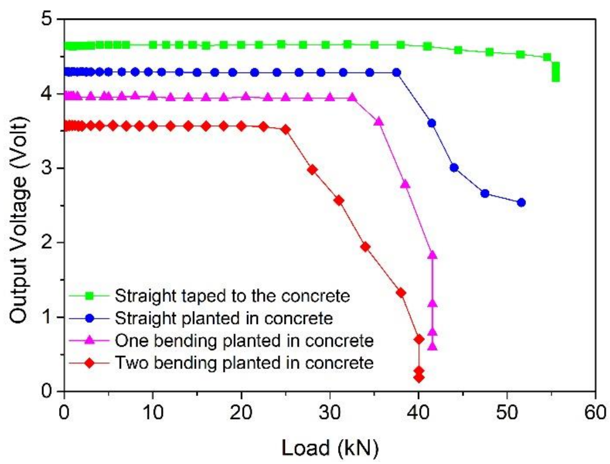

Figure 5. The output voltage changes to the load changes for concrete tensile test.

Figure 5 shows that the change in output voltage to the load changes is applied to a sensor based on POF with various configurations. In Figure 5, the green sign indicates a straight configuration taped to the concrete, for blue sign indicates a straight configuration planted in the concrete, for purple sign indicates one bending configuration planted in the concrete, and the last for red sign indicates two bending configurations planted in the concrete. The load and each configuration obtained a different response. In Figure 5, the output voltage for each measurement decreases significantly. It indicates the critical point of each measurement, and concrete begins to crack. The addition of the load causes the force and pressure on the concrete to increase so that the concrete begins to crack at the maximum load limit. Each sensor installed on the concrete has a different maximum load.

Similarly, the compressive strength of the concrete decreases proportionally to changing the sensor configuration. The highest tensile strength is obtained in the sensor configurations taped to the surface of the concrete with a maximum load of 55.5 kN. In contrast, the lowest compressive strength is on the sensor configuration with two bending and load value of 40.05 kN. In Figure 5, the drop values because bends and longer the length of the sensor that is embedded or planted in the concrete will reduce the compressive strength of the concrete have been tested. However, the sensitivity and resolution value of the sensor get better. Besides, the more optical fiber sensors embedded in the concrete greatly affect the tensile strength of the concrete, and the more optical fibers that are embedded in the concrete, the lower the tensile strength concrete.

Furthermore, when the concrete is given pressure indicates the increase of load. The increase of load causes the force to increase and implicate strain on the optical fiber or change in length and experiences both large and small indentations. The change is then causing loss of powers in the POF. The amount of power losses in the optical fiber sensor causes decreasing of the light intensity received by the phototransistor and output voltage to decrease.

The difference in output of the sensor will produce different range, sensitivity, and resolution values. This difference obtained for each sensor is due to differences in compressive and tensile of the sensor when there is a change in load on the concrete. This change will affect the sensitivity of that sensor become higher, and the resolution values will be better. Characteristic results of the output voltage with range, sensitivity, and resolution values vary according to the sensor configuration. Characteristics of sensors based on POF for compressive tests and concrete tensile tests are shown in Table 1.

Table 1. Sensor's characteristics based on POF for concrete compressive test and concrete tensile test.

Sensor Configuration	Range (Volt)		Sensitivity (Volt/kN)		Resolution (kN)		Load (kN)		Concrete Strength (MPa)	
	Com-pressive Strength	Tensile Strength	Com-pressive Strength	Tensile Strength	Com-pressive Strength	Tensile Strength	Com-pressive Strength	Tensile Strength	Com-pressive Strength	Tensile Strength
Taped to the concrete surface	0.752	0.405	0.009	0.007	0.402	0.548	75.500	55.500	9.610	1.760
Straight in the concrete	1.880	1.759	0.028	0.034	0.139	0.117	65.500	51.600	8.340	1.640
One bending planted in the concrete	1.988	3.170	0.037	0.076	0.105	0.052	52.500	41.550	6.680	1.320
Two bending planted in the concrete	4.051	3.290	0.085	0.082	0.047	0.048	47.200	40.050	6.010	1.270

Based on Table 1 shows that the range, sensitivity, and resolution value of the sensor are different in each configuration of either compressive strength or concrete tensile test. The best sensitivity and resolution values for sensors based on POF for concrete compressive tests are on two bending configurations planted in the concrete, with the values respectively 0.085 Volt/kN and 0.047 kN. Similarly, the concrete tensile test is also on two bending configurations planted in the concrete, with the sensitivity and resolution value of 0.082 Volt/kN and 0.048 kN, respectively. The measurement result can be seen in the comparison graph in Figure 6. This figure shows the comparison graph of the sensitivity value of compressive and tensile sensors with various configurations. It is seen that the highest sensitivity value in the two bending configurations planted in compressive concrete.

The sensor test worked to get the best characteristics, higher sensitivity and better resolution. The data from the compressive and tensile sensor testing produce a different response. The design of the sensor is made with two variations of sensor installation that is taped to a concrete surface or planted in concrete. For taped to a concrete surface using straight configuration. For the variation of POF that planted on concrete using three types of configuration are straight, one bend, and two bends planted in concrete. The best result of the compressive concrete sensor shows the best sensitivity and resolution are two bending planted in concrete with the values of 0.085 Volt/kN and 0.047 kN, respectively.

Furthermore, for the best result of the tensile concrete sensor is two bending planted in concrete with the sensitivity and resolution values of 0.082 Volt/kN and 0.048 kN, respectively. The results of this research indicate that sensors based on plastic optical fiber for concrete compressive tests show higher sensitivity and resolution compared with previous research reported in Ref [18] by using amorphous Ferromagnetic microwires based sensor. The sensor has been made from POF suitable to detect compressive and tensile in concrete structures because of high sensitivity, real-time measurement, and simple measurement process.

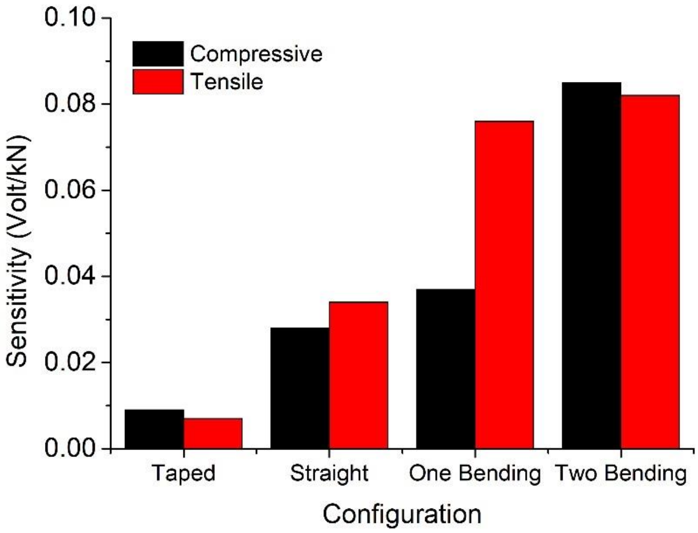

Figure 6. Comparison graph of sensitivity value at various configurations.

4. Conclusion

The sensor-based on POF is used for sensor testing of compressive and tensile in the concrete. The result shows that more bending on plastic optical fiber sensors causes greater power losses resulting in smaller output voltages on the computer. It causes better characteristics that impact the sensitivity and resolution values of the sensor to become better. The best characteristic result of the sensor based on the plastic optical fiber for concrete compressive is two bending planted in concrete, with the values of sensitivity and resolution of 0.085 volt/kN and 0.047 kN, respectively. While in the concrete tensile test with the best value of sensitivity and resolution are 0.082 volt/kN and 0.048 kN, respectively. The sensor has the advantage that is low cost and simple in measurement method that can be applied for monitoring the condition of the building structure.

Acknowledgements

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