Evaluation of The Mechanical Properties of Translucent Concrete

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Abstract *The last decade has witnessed a heightened interest in making buildings more sustainable, which has been fueled largely by the increase in energy costs and advancements in manufacturing technology. Lighting consumes a substantial amount of this energy, making it necessary to look for alternative technology that depends more on natural lighting. This study investigated a novel building envelope material that consists of optical fibers embedded in concrete. The paper discusses the mechanical effects of the inclusion of plastic optical fiber (POF) into self-compacting mortar (SCM), by producing special boards with dimensions (300×150×15mm), (300×150×25mm) and (300×150×50mm) with 4% POF volume fraction content and (2.0, 3.0mm) diameter, which could be used in many applications (ceilings, external walls, partitions, floor tiles, etc.). The experimental results show that an optical fiber can be easily combined with self-compacting mortar (SCM) but with very high skillness. The results indicated that the absorption values for boards with 15, 25 and 50mm thickness are increased by about (2.70, 2.92 and 3.2%) respectively, as compared with reference board and all results within requirement. Handleability index in translucent concrete boards decreases due to the inclusion of POF and the breaking moment between (189.90-1616.5Nm/m) for samples at 28-days age.*

Keywords — *translucent concrete board, plastic optical fiber, self-compacting mortar.*

I. INTRODUCTION

Translucent concrete is composed of two main components: the first is concrete, the common constituents in most important civil engineering applications. The other component is optical fiber that is normally used in sensing applications, and has good light guiding property that can be used to transmit light [1]. The optical fiber could transmit the light without any losses by using a type of optical fiber with high numerical aperture (NA) and large-diameter core. The numerical aperture (NA) that is equal to the sine of acceptance angle must have large value in order to keep the wave guide through the optical fiber without losses. The size of (NA) will depend on the reflective indices for core/cladding of material [2,3,4]. By combining the advantages of the concrete and optical fiber, the development of a novel functional material called “translucent concrete” has an important value in the application of construction and sensing [1]. Translucent concrete is also known as “transparent concrete” and “light transmitting concrete” because of its properties [1, 2, 5].

Natural sunlight is the best source for light which is actually free of cost. A room with translucent concrete walls in it would be brightly illuminated with natural sunlight, which is a requirement for green buildings. Also, these optical fibers work as heat insulators, so they will be very effective in cold and very hot countries, thereby reducing energy and saving considerable cost in both the cases.

Translucent concrete can also help add a great deal of security and supervision in places like schools, museums and prisons, etc., where there is the need to see the presence of people and their actions are seen but not their entire image, thereby protecting their privacy as well. In addition, translucent concrete has very good architectural properties for giving good aesthetical view to the building.

It is obvious that translucent concrete is a great tool in saving electricity and money as well. It’s stronger than glass and possesses almost the same characteristic strengths of normal concrete blocks, therefore is a better replacement to it [6].

II. ADVANTAGES AND DISADVANTAGES OF TRANSLUCENT CONCRETE

Translucent concrete is still under investigation and improvements. However, there are many advantages that could be listed for this type of concrete, they are mainly [1, 2, 6, 7]:

•Providing a solid wall with the ability to transmit light means fewer lights can be used inside the house during daylight hours which in turns results in energy saving.

•It has the architectural advantage of giving good aesthetical view to the building.

•Transparent concrete can be used where light is not able to be admitted properly to a certain closed place.

•Energy saving makes transparent concrete an environment friendly choice compared to conventional concrete.

The main disadvantages are:

• These concrete is it is high cost due to the use of the optical fibers.

•Casting of transparent concrete block is a difficult task for the labour and requires specially skilled workers.

III.EXPERIMENTAL WORK

A. *Materials*

The materials include a description of the cement, fine aggregate, mineral and chemical admixtures, and plastic optical fibers (POF) used in this research.

1) ***Cement:*** The cement used was Ordinary Portland Cement manufactured in Iraq. The cement was tested and checked according to IOS 5:1984 [8] Table 1 and 2 show the chemical properties and the physical properties of cement.

Table 1: Chemical composition of Portland cement.

Oxides composition	**Content %**	**Limits of Iraqi specification No.5/1984[8]**
CaO	61.12	---
SiO_2	20.18	---
Al_2O_3	5.00	---
Fe_2O_3	3.30	---
MgO	3.80	<5.00
SO_3	2.34	<2.80
L.O.I.	3.16	<4.00
Insoluble residue	0.14	<1.5
Lime Saturation Factor, L.S.F.	0.96	0.66-1.02
C_3S	50.40	---
C_2S	19.91	---
C_3A	7.67	---
C_4AF	10.03	---

Table 2: Physical properties of cement.

Physical Properties	**Test results**	**Limits of Iraqi specification No.5/1984[8]**
Specific surface area (Blaine Method), m^2/kg	330	≥230
Setting time (Vicat Apparatus), Initial setting, hr:min Final setting, hr:min	3.00 5.30	≥00:45 ≤10:00
Compressive strength, MPa 3 days 7 days	19.6 28.9	≥15.00 ≥23.00
Soundness (Autoclave Method), %	0.09	≤0.8

2) ***Aggregate:*** Al-Ekhaider natural sand was used in this research as the fine aggregate. All particles greater than 600µm and smaller than 150µm were removed by sieving. The sand grading and the sulfate content were within the requirements of the IOS No.45/1984 [9] in Table 3 and the results of chemical and physical properties of the sand used show that the specific gravity, absorption %, dry loose-unit weight kg/m^3, sulfate content as SO_3 are 2.60, 2.00%,1595kg/m^3, and 0.24% respectively.

Table 3: Grading of sand compared with requirements of Limits of IOS No.45/1984 [9].

Sieve size (mm)	**Cumulative passing%**	**Limits of IOS No.45/1984 [9]**
10.00	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.60	100	80-100
0.30	57.3	15-50
0.15	0	0-15

3) ***Water:*** Tap water was used for both the mixing and the curing of composite products.

4) ***Mineral Admixture:*** Densified silica fume was used as a partial replacement of cement (10% by wt.) in this study Table 4 shows some of the properties of a similar product.

Table 4: Chemical analysis of the silica fum.

Oxide composition	Oxide content %
SiO_2	94.10
Al_2O_3	0.38
Fe_2O_3	0.01
Na_2O	0.00
K_2O	0.07
CaO	1.20
MgO	0.15
SO_3	0.22
L.O.I.	3.87

The Pozzolanic Strength Activity Index (P.S.A.I.) of Silica Fume: Reference and silica fume mortars have been prepared for the pozzolanic activity index (P.S.A.I.) measurement. All mortars consisted of 1 part of cement or cementitious materials and 2.75 parts of graded standard sand by weight. The cement mortar of the test mix incorporated 10% of silica fume as a partial replacement by weight of cement as recommended by ASTM C1240-03 [10]. The test results are shown in Table 5.

Table 5 Physical requirements of silica fume.

Physical properties	**S.F.**	**Limit of specification Requirement ASTM C 1240**

Percent retained on 45µm (No. 325) sieve,%	7	Max. 10
Accelerated Pozzolanic Strength Activity Index with Portland cement at 7 days,%	196	Min. 105
Specific surface,m^2/g	20	Min. 15

5) ***Chemical Admixture:*** (High range water reducing admixture) One of the generations of Polycarboxylic ether-based superplasticizer, designed for the production of SCM was used (Glenium 51). Table 6 shows the main characteristics of the product.

Table 6: Typical properties of (Glenium 51).

Main action	Concrete super plasticizer
Color	Light brown
PH. Value	6.6
Form	Viscous liquid
Subsidiary effect	Hardening
Relative density	1.082 - 1.142 kg/liter
Viscosity	128 ± 30 cps at 20°C

6) ***Plastic optical fiber:*** The Plastic Optical Fibers is PMMA (Poly Methyl Methacrylate) fibers manufactured by a specialized company, with different diameters of (POF) were used (2.0 and 3.0mm). Table 7 show the properties of POF and Table 8 show the details of the POF.

Table (7): Typical properties of (POF).

The typical properties	Characters
Fiber material	Poly Methyl Methacrylate PMMA
Fiber diameter	1.5mm 2.0mm 3.0mm
Length for: 1.5mm 2.0mm 3.0mm	700m/roll 350 m/roll 250 m/roll
Quality	good quality
Light reduction	250dB/km
N.A Operation temp °C	0.5 (50~+70)
Temperature in storage	20°C - 50°C
Allowable working temperature range	- 50°C - +70°C
Advantages	Virtually no heat, No electrical hazard
Clad refractive index	1.402
Wavelength range	390-760nm
Allowable bending radius	8times diameter

Table 7: No. of (POF) in the three types of boards.

Dimension of the board(mm)	Diameter of (POF)(mm)	No. of (POF)
(300×150×15mm)	2.0	557
(300×150×25mm)	2.0	557
(300×150×50mm)	3.0	250

B. Mix proportions, Casting and Preparation of Samples

After many trail mixes the adopted mix used in this study to produce a SCM estimated in kg/m3 are listed as below:

Portland cement – type I = 495 kg/m^3.
•Natural fine sand (150 – 600 µm) = 1375 kg/m^3.
•Densified silica fume = 55 kg/m^3.
•Water = 247.5 kg/m^3.
•Superplasticizer (Glenium 51) = 20 kg/m^3.

Then the wooden molds shown in Fig.1 have been oiled properly for easy de-molding.

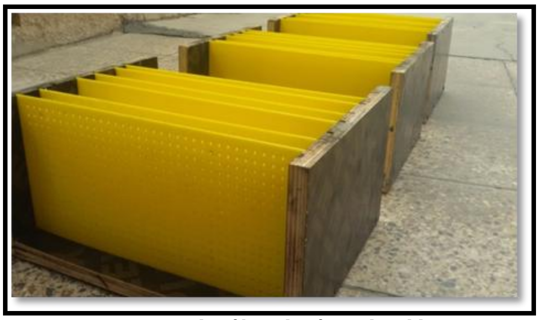

Fig. 1: Details of boards of wood mold

The molds were fully and carefully filled with one layer as shown in Fig. 2. No vibration instrument was used for compacting the mix, because self-compacting mortar mix tends to flow under its own weight. The finishing needs to be carried out as soon as possible after the correct level is reached and before stiffening starts and any surface drying occurs. Initial curing should therefore start as soon as possible after the placing and finishing. A plastic sheet was used in order to minimize the risk of surface crusting and shrinkage cracks caused by early age moisture evaporation [11, 12].

Fig. 2: The specimens in mold

After 48 hours the hardened specimens have been de- molded, and cured in water tank with temperature 23±2 C° for 7 and 28 days. Fig. 3 shows the boards after 28 days curing.

Fig. 3: Translucent Concrete Boards

C. Tests of concrete

1) Fresh concrete Tests:

For each mix, the fresh properties are evaluated and compared with the requirements of SCM. We have previously conducted workability tests on fresh concrete immediately after mixing. The tests included slump flow test and V-funnel test, and their results are reported elsewhere [13].

These results are within the acceptable criteria for SCM EFNARC, 2002 [14] and also indicate a homogeneous mix without segregation.

2) Hardened Properties tests on concrete samples and produced Boards:

We have previously conducted several destructive and non-destructive hardened properties tests to evaluate the performance of Translucent Concrete with age. [11] The product obtained in that study with a high percentage (4% of POF), was used to produce the translucent concrete boards in the present study, with three different dimensions according to ASTM C1185-03[15]. The dimensions of the boards match those used in ceilings, partitions and walls. All of this samples were tested to determine their Flexural Strength, Flexural Toughness, Modulus of toughness and Density [12], Handleability Index, Breaking Moment and Water Absorption.

Handleability Index: The handleability index test has been at 28-days age conducted on the boards with dimensions (300 × 150 × 15mm), (300 × 150 × 25mm) and (300 × 150 × 50mm) under central line loading according to ASTM C1185-03[15] using flexural testing machine with 50 kN capacity (see Fig. 4). The Handleability index value is used to determine the capability of the material to be handled without breaking. An increase in handleability index means increased ease of handling. The average of three boards was taken at 28-days age to calculate the handleability index according to ASTM C1185-03 [15] using equation (1).

$$U = \frac{0.5P\Delta}{t} \qquad (1)$$

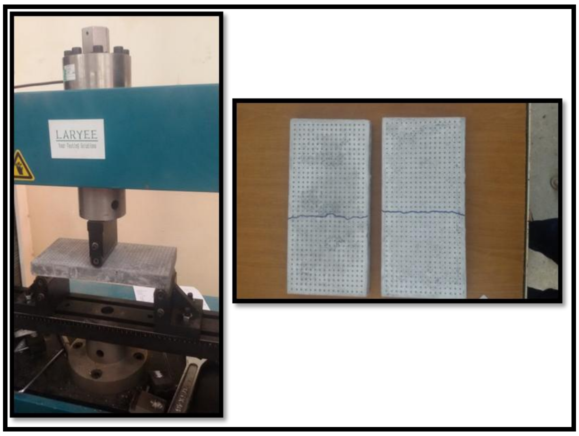

Fig. 4: The tested boards.

Breaking Moment: The Breaking Moment test is performed for the obtained product (board) according to ASTM C1185-03[15], and is done only on the products of dimensions (300 × 150 × 15mm) with and without plastic optical fiber. The breaking moment refers to ability of roofing to bearing the load without breaking. Therefore, the main factors that affect the breaking moment in this test are the maximum load applied on the mid-span of the board and the span length. The results have been obtained as the average of three tested samples at 28-days age, and the Breaking Moment was calculated using equation (2).

$$M = \frac{PL}{4b} \qquad (2)$$

Water Absorption: According to the ASTM C1185-03[15], and as shown in Figure 7 and Figure 8, the average water absorption of the produced boards is measured using the three types of boards, which were of different thicknesses, (15, 25 and 50mm).

The age of boards is 28 days, and they are with and without POF. Equation 3 is used to determine the water absorption of the samples.

Water Absorption $=[(W_S-W_d))/(W_d]\times 100)$ (3)

Where:

Ws: Saturated mass (g) of the sample.

Wd: Dry mass (g) of the sample.

Fig.7: The suspended weight test machine.

Stress-strain Behaviour for Translucent Concrete: The static modulus of elasticity under tension or compression is given by the slope of the stress–strain curve for concrete under uniaxial loading. However, this curve for concrete is nonlinear and the elastic characteristic of a material is a measure of its stiffness [16].

Therefore, stronger concrete has greater static modulus of elasticity [17]. The Modulus of elasticity of concrete is a very important parameter expressing the capacity of concrete to deform elastically. The modulus of elasticity is relevant to cracking because for a given strain, a higher modulus produces a higher tensile stress, which means that stronger concrete exhibits a lower strain.

IV. RESULTS AND DISCUSSION

From the fresh mixes test, it can be concluded that; it is possible to produce mortar mixes having a self-compacting ability with slump flow D (mm) and V-funnel Tv (sec) of (255mm) and (7.3sec), respectively. The proposed mix proportion are (1:2.5:0.45) and 10% silica fume as a replacement by weight of cement content with all mixes.

Absorption: According to the ASTM C1185-03[15], the absorption of translucent concrete boards is determined and compared with the requirement. The produced boards are of different thicknesses, (15, 25 and 50mm) and various diameters POF (2.0mm and 3.0mm). The tested results are compared with a reference board of the same thickness, but without POF. Fig. 8 shows that the absorption of the translucent concrete boards is (2.70), (2.92) and (3.2%) for board thickness (15), (25) and (50 mm) respectively, while the absorption of the reference board (without POF) for the same thicknesses are (1.50), (1.37), and (1.11 %), respectively. It is clear that the boards with 4% POF volume fraction have higher absorption than mixes without fiber. That means that the inclusion of POF leads to the formation of pores or micro cracks and hence increases the absorption and reduces the density. The smooth nature of the surface of POF weakened the bond in the interfacial transition zone between the matrix and the POF.

The translucent concrete board with 50mm thickness and 3.0mm POF diameter had the highest absorption value (3.2%), due to its large thickness compared to the (15 and 25mm) thickness, and the larger surface area of the POF used in this board compared to the (15 and 25mm) thickness of boards that used POF with 2.0mm diameter.

Handleability Index: These results indicate that the handleability index in translucent concrete boards decreases due to the inclusion of POF. For example, the handleability index of 50 mm thickness of board with and without POF are (26.87) and (29.94 mm,N/mm), respectively. The reduction in handleability index is (10.25%).

The increase in handleability index means the increase in the ease of handling. Fig. 9 shows that the board with 50mm board has the highest value for the two cases (with and without POF) due to the high breaking load of the 50mm board compared to the boards with (15) and (25mm) thickness.

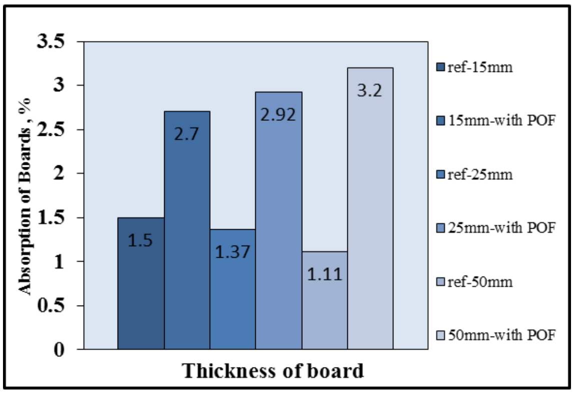

Fig. 8: Absorption results for all type of translucent boards and their references tested of 28 days of curing.

Breaking Moment: The breaking moment refers to ability of roofing to bear the load without breaking. Therefore, the main factors that affect the breaking moment in this test are the maximum load applied on the mid-span of the board and the span length. The average test results indicate that the breaking moment of the translucent concrete board decreases by about (33.7%) compared to boards without POF. This reduction due to the inclusion of POF should be considered during the production of all types of boards.

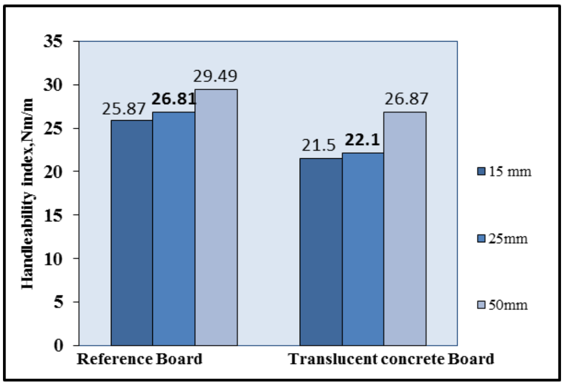

Fig. 9 Relationship between the Handleability Index and the thickness of boars tested at 28-days age.

Stress-strain Behaviour for Translucent Concrete: The stress–strain diagram for all types of boards are plotted in Fig. 10 to Fig. 12. From these figures, the static modulus of elasticity decreases in translucent concrete for all types of boards due to the embedment of POF in the mortar, the POF has a small modulus of elasticity that is lower than $2.1*10^{-2}$ GPa [18]. The POF increases the porosity in mortar, which leads to the decrease in the modulus of elasticity, and this is in agreement with (Mehta) [19] and (Neville) [20].

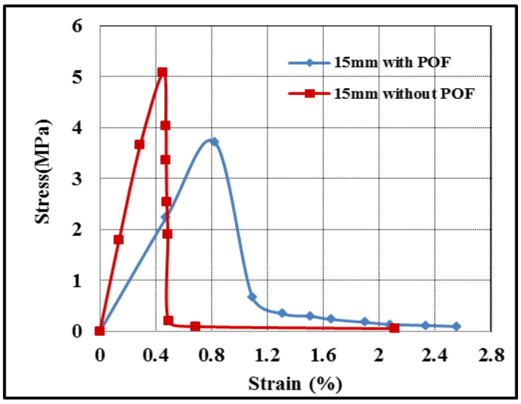

Fig. 10: Stress-strain behaviour for translucent concrete board.

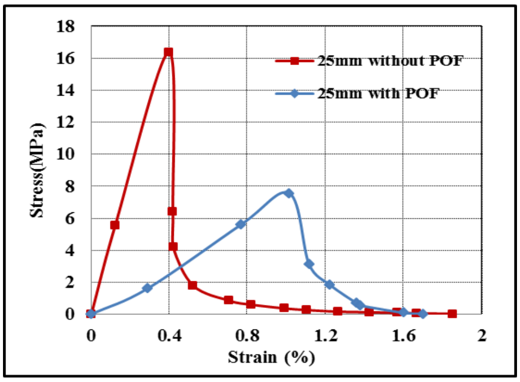

Fig. 11: Stress-strain behaviour for translucent concrete board.

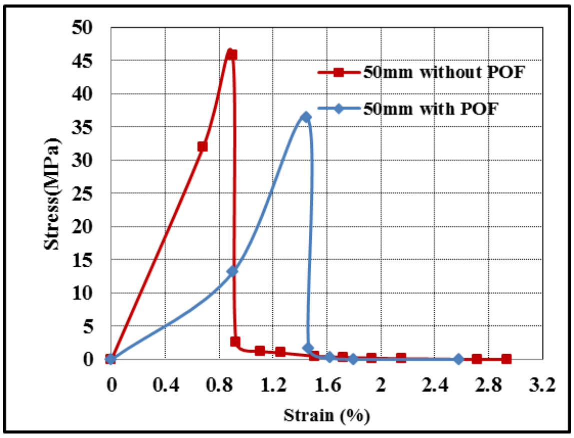

Fig. 12: Stress-strain behaviour for translucent concrete board.

V. CONCLUSIONS

From the discussion of the tests results the following conclusion could be drawn:

1. A novel architectural material called translucent concrete can be produced by adding optical fiber (POF) in the SCM mixture. The fabrication process of standard translucent concrete requires a very high skill during the preparation of the molds, and the arrangement and alignment of the (POF) according to its content.
2. The inclusion of POF increased the absorption percentage and decreased the density of the concrete.
3. The inclusion of POF also caused the reduction in the handleability index and breaking moment due to the nature of POF surface which cause the "debonding" and weakening of the interfacial transition zone between the POF surfaces and SCM (the matrix).
4. The ductility increases with the inclusion of POF to SCM mixture. This is attributed to the fact that mixes that contain POF have higher ability to show strain as compared with mixes without POF due to (POF).

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