Design of Glass Reinforced Concrete Wall for Improved Utilisation of Natural Light and Aesthetics without Compromising the Strength

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Abstract

The main purpose of this research was to use sunlight as a light source in order to reduce the power consumption of illumination inside buildings while enhancing aesthetics. Translucent concrete is a concrete based material with light-transmissive properties, obtained by embedding light optical elements like optical fibres in it and glass liquor bottles. Light is then conducted through the stone from one end to the other. Light transmitting concrete, also known as translucent concrete and is made by switching the ingredients of traditional concrete with transparent ones or embedding fibre optics. In this paper optical fibres were used to transmit light through fibre. This smart translucent concrete can be used as a green energy saving construction material. It is a promising technology for field applications in civil engineering.

Keywords

Reinforced concrete, concrete strength, fibre glass

1. Introduction

The world is moving towards much more utilisation of renewable energy sources and Zimbabwe has problem of producing enough power required in the country. Therefore, it is necessary to design buildings that will require less and less of the power coming from the grids by utilising natural light, a non-depletable source. This research is promoting improved lighting using natural light, thereby reducing the use of light from non-renewable sources during the day. This is a plus in the tobacco selling industry where they use the natural sunlight to see the condition of the tobacco brought in by farmers. This will assist with the utilisation of alcohol glass bottles that are ordinarily not recycled. These bottles can be embedded in concrete to produce a wall which will allow light to pass through the walls. Reinforcing concrete with glass fibre increases the tensile strength of the concrete. The embedded glass fibre is usually alkaline and hence resistant to wear due to acid rain and other acidic materials. Added to these advantages glass reinforced concrete is also fire resistant, weather resistant, low thermal conductivity and long lasting (White, 2007). It also offers a variety of shapes for exterior surfaces or interior surfaces as partition walls.

2. Literature Review

2.1 Concrete and Its Components

Concrete is an artificial conglomerate stone made essentially of Portland cement, water, and aggregates. Some of these aggregates include sand and gravel. Portland cement makes up the greatest composition in cement and is made from quarry and it is produced by putting together ground limestone, clay or shale, sand and iron ore. This mixture is placed in a rotary kiln and heated to temperatures which can be as high as 1600 degrees Celsius or more (Shetty, 2000). Water and cement can be mixed to produce a paste which surrounds all the individual pieces of aggregate to make a plastic mixture. Anhydrous cement cannot bind fine and coarse aggregate. The adhesive property of cement results from its mixture with water through a chemical process known as hydration. The chemistry of concrete is essentially the chemistry of the reaction between cement and water. Products of hydration are important as they have cementing or adhesive value (Shetty, 2000).

2.2 Concrete Aggregates

These make up most of the concrete, up to about seventy percent of the concrete. They can be classified as Normal weight aggregates, Light weight aggregates and Heavy weight aggregates. Normal weight aggregates are the mostly used and the other two are used in special scenarios. The Normal weight aggregates can be further divided into natural and artificial aggregates. Most natural aggregates come from bed rocks, that is igneous, sedimentary and metamorphic rocks. Aggregates from igneous rocks are normally hard, tough and dense. These aggregates are mostly reactive and have a tendency to chemically react with alkalies of cement as they are mostly acidic. According to (Rozalija Kozul, David Darwin, 1997) changes in coarse aggregate can affect the strength of concrete and fracture properties, it is therefore essential to understand the aggregate type and size so as to predict results on concrete loading. Experiments by (Ezeldin, A. S. and Aitcin, P.-C., 1991) concluded that, in high-strength concretes, higher strength coarse aggregates typically yield higher compressive strengths, while in normal-strength concretes, coarse aggregate strength has little effect on compressive strength. In concretes containing basalt, load induced cracks developed primarily at the matrix-aggregate interface, while in concretes containing limestone, nearly all of the coarse aggregate particles were fractured.

2.3 Water/Cement Ratio

The single most important indicator of strength is the ratio of the water used compared to the amount of cement (*w/c* ratio). Basically, the lower this ratio is, the higher the final concrete strength will be. This concept was developed by Duff Abrams of The Portland Cement Association in the early 1920s and is in worldwide use today. Water/Cement Ratio. A minimum *w/c ratio* (water-to-cement ratio) of about 0.3 by weight is necessary to ensure that the water comes into contact with all cement particles (thus assuring complete hydration). Typical values are in the 0.4 to 0.6.

2.4 Concrete curing and compressive

Maintenance of a satisfactory moisture content and temperature in concrete for a suitable period of time immediately following placing & finishing so that the desired properties may develop. Factors that affect curing are time, temperature and moisture.

2.5 Glass as a structural material

Glass is not used as often as it should as a structural material. The main reason being that it is perceived to be more fragile and dangerous that it really is. Glass designed for structures can withstand loads higher than steel. The process used in the manufacturing of the glass is at the root of the strength of the glass, as well as the material properties. (White, 2007).

2.6 Optical Fiber

it is a flexible, transparent fiber made up of glass or plastic. It transmits light from one end to the other of the optical fiber. Use of optical fiber is a reliable and effective way of transmitting light that there is almost no loss of it conducted through the fibers. For light transmission the thickness of optical fiber should be varied from 2 μm and 2 mm. An example of optical fiber is shown below. Types of optical fibre include:

- Multimode Fiber
- Single-mode Fiber
- Multimode Step-index Fiber
- Multimode Graded-index Fiber

These different types of optical fibers are distinguished from each other by the way the light is reflected.

2.7 Transparent Concrete as an Eco-Friendly Material for Building

Concrete has changed considerably in technical and aesthetic terms. It is no longer the heavy, cold and grey material of the past; it has become beautiful and lively (Bhavin K. Kashiyani, Varsha Raina, Jayeshkumar Pitroda, Dr. Bhavnaben K. Shah, 2013). Transparent concrete focuses on green technology and artistic finish. There are two basic materials used for making transparent concrete which are concrete and optic fibre. Transparent concrete can be made by arranging the high numerical aperture Plastic Optical Fibres (POF) or big diameter glass optical fiber into concrete (Dinesh W. Gawatre , Suraj D. Giri , Bhagwat B. Bande, 2016).

3. Development of Possible Design Options

The designs are made in such a way that they best address the research objectives. Finite element analysis was done using Autodesk Inventor to come up with the best solution. All solutions were subjected to a 20MPa stress which is the maximum compressive stress concrete should sustain.

3.1 Possible Solution 1

In this solution a block of glass fibre reinforced concrete with an empty glass liquor bottle at the centre is designed. This is shown in Figure 1.

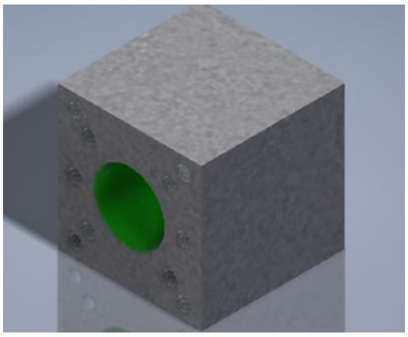

Figure 1: Solution 1

A. Finite Element Analysis Report

Below is a summary of the finite element analysis report. Summary
Physical properties are highlighted in Tables 1 to 5.

Table 1: Physical

Mass	0.192002 kg
Area	36808.9 mm^2
Volume	107815 mm^3
Center of Gravity	x=-3.33333 mm y=-3.87848 mm z=0 mm

B. Static Analysis

The analysis will be static and single point. The table below summarises the objective and settings of the analysis. The table below shows the mesh settings used for finite element analysis.

Table 2: Mesh Settings

Avg. Element Size (fraction of model diameter)	0.1
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	No
Use part based measure for Assembly mesh	Yes

The materials under analysis are highlighted in the materials table. The specific properties of each material are also indicated in the table. The table also states the name used by the researcher for each component used.

Table 3: Materials

Name	GFRC	
General	Mass Density	1.7 g/cm^3
	Yield Strength	4.96 MPa
	Ultimate Tensile Strength	6.89 MPa
Stress	Young's Modulus	10.5 GPa
	Poisson's Ratio	0.24 ul
	Shear Modulus	4.23387 GPa
Part Name(s)	block 2.ipt	
Name	Glass	
General	Mass Density	2.18 g/cm^3
	Yield Strength	33 MPa
	Ultimate Tensile Strength	33 MPa
Stress	Young's Modulus	68 GPa
	Poisson's Ratio	0.19 ul
	Shear Modulus	28.5714 GPa
Part Name(s)	glass 1.ipt glass 3.ipt	

The conditions in which the block will operate are highlighted below. The block will be subjected to a pressure force only for this analysis.

Table 4: Operating Condition

Load Type	Pressure
Magnitude	25.000 MPa

The table below indicates maximum and minimum values of each of the static conditions of the block when it was subjected to 20Mpa.

Table 5: Maximum and Minimum values

Name	**Minimum**	**Maximum**
Volume	107815 mm^3	
Mass	0.192002 kg	
Von Mises Stress	3.91021 MPa	107.735 MPa
1st Principal Stress	-7.15125 MPa	45.6753 MPa
3rd Principal Stress	-106.108 MPa	0.552148 MPa
Displacement	0 mm	0.092815 mm
Safety Factor	0.131351 ul	6.53893 ul
Stress XX	-20.8345 MPa	45.66 MPa
Stress XY	-8.08658 MPa	8.06293 MPa
Stress XZ	-15.6474 MPa	15.606 MPa
Stress YY	-9.58324 MPa	16.4866 MPa
Stress YZ	-9.84023 MPa	9.71348 MPa
Stress ZZ	-106.107 MPa	9.13793 MPa
X Displacement	-0.021049 mm	0.0210581 mm
Y Displacement	-0.0132658 mm	0.0133919 mm
Z Displacement	-0.0928149 mm	0 mm
Equivalent Strain	0.0000646801 ul	0.00337151 ul
1st Principal Strain	-0.0000244086 ul	0.00187191 ul
3rd Principal Strain	-0.00404134 ul	-0.0000204465 ul
Strain XX	-0.000968524 ul	0.0018584 ul
Strain XY	-0.000451917 ul	0.000451383 ul
Strain XZ	-0.00140523 ul	0.00140211 ul
Strain YY	-0.000202515 ul	0.000973605 ul
Strain YZ	-0.00110782 ul	0.00112028 ul
Strain ZZ	-0.00377412 ul	0.000138217 ul
Contact Pressure	0 MPa	75.974 MPa
Contact Pressure X	-75.0029 MPa	72.0777 MPa
Contact Pressure Y	-32.0372 MPa	21.8535 MPa
Contact Pressure Z	-66.6947 MPa	70.9783 MPa

3.2 Solution 2

A similar block was used but this time concrete is filled within the glass. This is shown below.

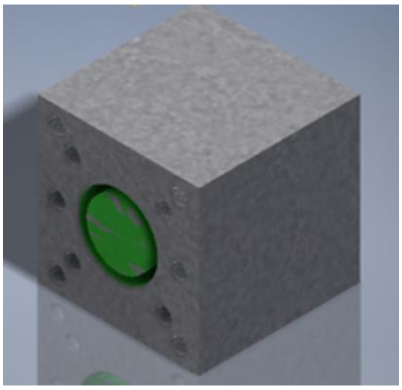

Figure 2: Solution 2

A. Finite Element Analysis Report

Below is a summary of the finite element analysis report. Table 6 shows the physical properties of the solution.

Table 6: Physical

Mass	0.224314 kg
Area	41025 mm^2
Volume	126822 mm^3
Centre of Gravity	x=29.0227 mm y=14.5879 mm z=-51.0314 mm

Note: Physical values could be different from Physical values used by Finite Element Analysis reported below.

B. <u>Static Analysis:2</u>

The analysis will be static and single point. Table 7 summarises the objective and settings of the analysis.

Table 7: General objective and settings

Design Objective	Single Point
Study Type	Static Analysis
Last Modification Date	25/10/2018, 11:46
Detect and Eliminate Rigid Body Modes	No
Separate Stresses Across Contact Surfaces	No
Motion Loads Analysis	No

Table 8 shows the mesh settings used for finite element analysis.

Table 8: Mesh Settings

Avg. Element Size (fraction of model diameter)	0.1
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	No
Use part based measure for Assembly mesh	Yes

The materials under analysis are highlighted in the materials table. The specific properties of each material are also indicated in table 9. The table also states the name used by the researcher for each component used.

Table 9: Materials

Name	GFRC	
General	Mass Density	1.7 g/cm^3
	Yield Strength	4.96 MPa
	Ultimate Tensile Strength	6.89 MPa
Stress	Young's Modulus	10.5 GPa
	Poisson's Ratio	0.24 ul
	Shear Modulus	4.23387 GPa
Part Name(s)	block 2.ipt cylindrical block.ipt	
Name	Glass	
General	Mass Density	2.18 g/cm^3
	Yield Strength	33 MPa
	Ultimate Tensile Strength	33 MPa
Stress	Young's Modulus	68 GPa
	Poisson's Ratio	0.19 ul
	Shear Modulus	28.5714 GPa
Part Name(s)	glass1.ipt glass 3.ipt	

The conditions in which the block will operate are highlighted in Table 9. The block will be subjected to a pressure force only for this analysis.

Table 9: Operating Conditions

Load Type	Pressure
Magnitude	25.000 MPa

Table 10 below shows how the different materials are bonded on the concrete block. The six different bonds are shown in the table below.

Table 10: How the different materials are bonded on the concrete block

Name	**Minimum**	**Maximum**
Volume	126822 mm^3	
Mass	0.224314 k	
Von Mises Stress	2.82439 MPa	59.7124 MPa
1st Principal Stress	-7.18798 MPa	12.0799 MPa
3rd Principal Stress	-59.6044 MPa	-2.34569 MPa
Displacement	0 mm	0.0847982 mm
Safety Factor	0.168434 ul	7.5545 ul
Stress XX	-59.6022 MPa	2.43985 MPa
Stress XY	-7.61581 MPa	8.39079 MPa
Stress XZ	-11.3381 MPa	11.2073 MPa
Stress YY	-8.25316 MPa	11.9863 MPa

Stress YZ	-3.09713 MPa	2.95406 MPa
Stress ZZ	-13.9491 MPa	9.45086 MPa
X Displacement	0 mm	0.0825758 mm
Y Displacement	-0.0105845 mm	0.0108923 mm
Z Displacement	-0.0174903 mm	0.0174888 mm
Equivalent Strain	0.0000529827 ul	0.00253283 ul
1st Principal Strain	0.000000980205 ul	0.00122483 ul
3rd Principal Strain	-0.00305358 ul	-0.0000509178 ul
Strain XX	-0.00294447 ul	0.0000653275 ul
Strain XY	-0.000763314 ul	0.000722025 ul
Strain XZ	-0.00102793 ul	0.00103471 ul
Strain YY	-0.0000843208 ul	0.000878595 ul
Strain YZ	-0.000276596 ul	0.000273821 ul
Strain ZZ	-0.000359785 ul	0.001174 ul
Contact Pressure	0 MPa	52.7088 MPa
Contact Pressure X	-52.442 MPa	47.907 MPa
Contact Pressure Y	-14.1032 MPa	12.4781 MPa
Contact Pressure Z	-10.0328 MPa	10.226 MPa

From the Finite element analysis solution 2 is selected as the chosen solution as it can sustain the 20MPa standard compressive strength much better than the first solution. From the detailed report in the appendix it showed that larger values of stress, displacement and strain are needed to cause failure in solution 2 than in solution 1.

4. Development of chosen solution

Procedures to come up with a glass reinforced concrete block are highlighted below and figures drawn using Autodesk Inventor are shown for the different stages.

4.1 Step 1

Two liquor bottles of different diameters were collected and cut to a same length using a glass cutter. The smaller diameter glass bottle is filled with fine concrete referred to onwards as cylindrical mould. After curing and drying the glass bottle with concrete is inserted in the larger diameter glass bottle as shown in Figure 3.

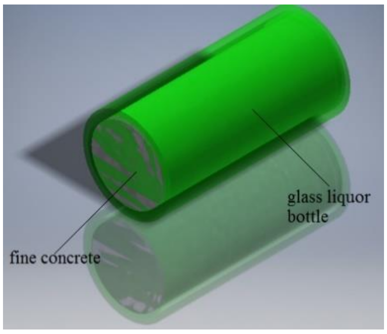

Figure 3: cylindrical mould

4.2 Step 2

The researcher used a 300mm sized cubic wooden block to create a cubic mould for the concrete block. Ten 15mm holes were drilled to insert the optic fibre and a 120mm hole is drilled at the centre of the cube. Figure 4 shows the mould.

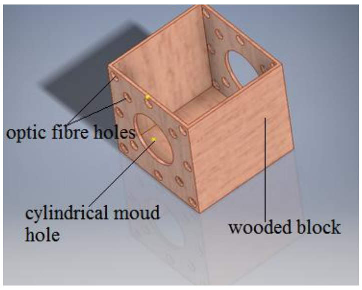

Figure 4: Cubic mould

4.3 Step 3

The researcher cut the optic fibres to a length size of the cube and coiled the optic fibre cables into optic fibre strands. The resultant fibre strand is shown in figure 5.

Figure 5: Optic fibre strand

4.4 Step 4

The researcher then inserts the optic fibre strands and the cylindrical glass mould in their respective holes on the cubic mould. This assembled mould is the one in which mixed concrete is added to. The researcher then filled the bottom of the mould with concrete. Fine aggregates were used to ensure that the optic fibre is not damaged in the process. Below is Figure 6 showing the assembled mould.

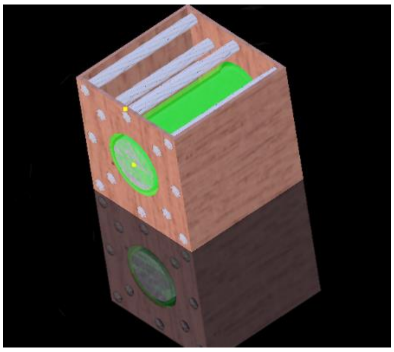

Figure 6: Assembled mould

4.5 Step 5

The final stage involves removing the concrete from the mould by using a saw to cut off the mould. Water is then added to the concrete for curing 12 hours after drying and the resulting block is shown in Figure 7.

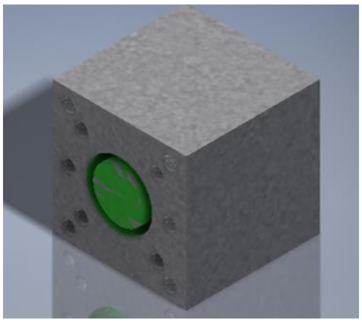

Figure 7: Glass reinforced concrete block

4.6 Comparison of amount of light

To compare the amount of light passing through the glass and through the glass fibre a paper was placed below the concrete block prototype and light source placed on top of prototype. Because the eye was used by the researcher for observations parameters dim and bright were used to determine the light intensity. Circles were drawn over the area in which the light passed through the glass bottle and diameter lines were drawn over the area in which light passed through the optic fibre. The percentages of the light intensities over the same area were then compared for the optic fibre and for the glass. The pictures in Figure 8 show how the experiment was done.

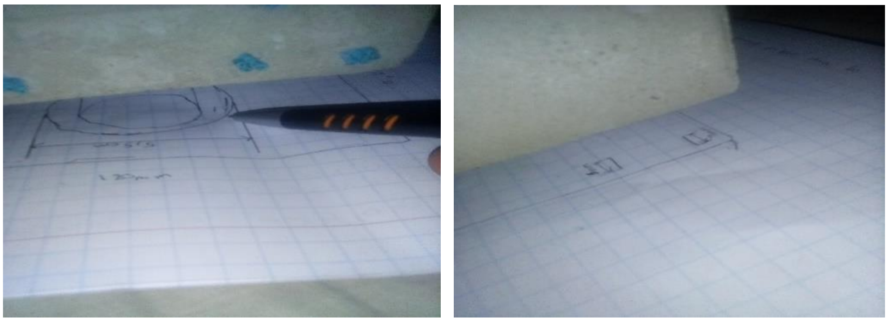

Figure 8: Measurement of light through the glass bottle and through the optic fibre

The calculations to follow in the appendix B show that over the same area 24% of it is covered by light passing through the optic fibre and 13% was covered by light through the glass bottle. Figures 9 and 10 show the 2D view of the chosen solution

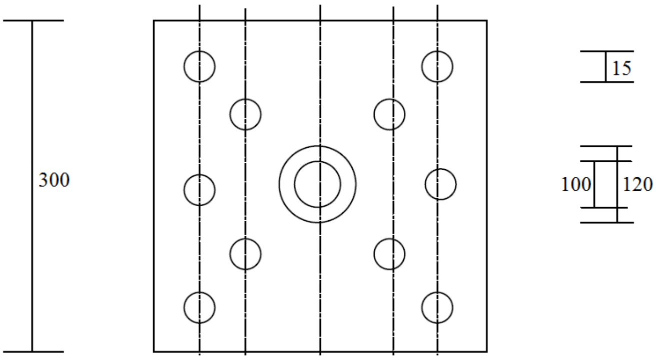

Figure 9: Plan

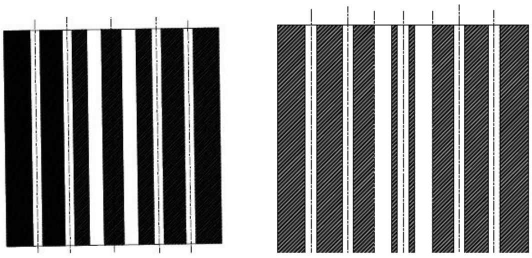

Figure 10: Front View and Side View

4.7 Material costing

The costs incurred buying materials to come up with a glass reinforced concrete block are highlighted in the table below.

Table 5.1: Material cost

Material	Cost($USD)
Optic fibre(8m)	2.40
Cement(2kg)	0.24
Wooden Block	1.00
Aggregates(4kg)	0.20
Total	3.84

4.8 Calculation of energy saved

To calculate the amount of energy saved by using GFRC from use of bulbs during day light hours a room made of a glass reinforced wall will be compared to room made of ordinary brick wall.
Taking the room to be 2700mm in height and a floor area of 3000*3000mm^3. The room is assumed to have a ceiling.
Area of wall = (2700*3000) mm^3
= 8100000 mm^3
Window area = (1500*950) mm^3
= 1425000 mm^3
Door area = (2050*870) mm^3
= 1783500 mm^3
Wall area available = [8100000-(1783500+1425000)] mm^3
= 4891500 mm^3
Area of one block = (300*300) mm^3
= 90000 mm^3
Number of blocks needed = $\left(\frac{4891500}{90000}\right)$
= 54.35
= 55 blocks
Price for room wall using GFRC = (55*3)
= $165
Each GFRC block has a size equal to three times that of an ordinary 70*230 brick and each brick costs $0.50
Price for room wall using ordinary bricks = (55*1.50)
= $82.50
Given that the room uses a 60Watt bulb and assuming eight hours of daylight use:
Amount of energy used = (8*0.06)
= 0.48kWh
Monthly energy used by the bulb = (0.48*30)
= 14.4kWh
1kWh of electricity costs $0.10 in Zimbabwe
Monthly cost of one bulb = (14.4*0.11)

= \$1.58

Using light transmitting concrete for our walls will thus save us about 14 kWh a month which is about \$1.60 of money a month which is about \$13 a year.

In 15 years, price of GFRC wall on the same room remains the same but for an ordinary brick wall which uses a 60Watt bulb during daylight hours the cost as a result of bulb use increases by: [82.50+(13*15)]

=\$277.5

This is \$112.5 more than for a GFRC wall which will be using natural light and increases daily.

5. Conclusion and Recommendations

5.1 Conclusions

The glass reinforced concrete block minimum flexural strength was defined through calculations and literature review of existing designs. Light transmittance in optic fibres was found to be greater than the transmittance through the glass liquor bottles by comparing light passing through a sample with glass or optic fibre to a sample without the glass or glass fibre. Finite element analysis proved that adding 2-3% of optic fibre without affecting the strength of concrete and maintaining the concrete strength within the standard M_{20} concrete grade. The same percentage of optic fibre in combination with glass a liquor bottle (cylindrical mould) improves light penetration through concrete walls. Also, the light passing through the glass was found to be dimmer than the light passing through the optic fibres. The only setback with using glass fibre to reinforce concrete is its cost but that is arguably outweighed by the improved aesthetics it gives to walls as well as the ability to save energy using sunlight, a renewable resource for lighting.

5.2 Recommendations

However, improvements can be made to the light transmitting concrete to archive better results in line with objectives. Melting the glass liquor bottles and molding them into glass rods will improve both compressive strength and light transmittance of concrete. To obtain transparency in concrete walls the optic fibre can be arranged in a mesh.

6. References

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Biography

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Charles Mbohwa is currently a Full Professor of Sustainability Engineering and Engineering Management at the University of Johannesburg, South Africa. He did his PhD in Engineering in Environmental Impact Assessment of Information and Communication Technology, Department of Information, Production and Systems Engineering, Tokyo Metropolitan Institute of Technology, Tokyo, Japan. Graduated in March 2004.