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ABSTRACT

Although concrete has been used extensively as a structural material for buildings since ancient times, light-transmitting concrete (LTC), also referred to as translucent concrete, is an innovative and attractive building material for the construction industry to enhance aesthetic and energy-saving properties. This research paper aims to investigate the mechanical properties of LTC with different optical fiber arrangements with three optical fiber ratios, respectively, 1, 1.6, and 2.4 %. The durability performance of LTC under the effects of accelerated aging is also investigated. Polymethyl methacrylate (PMMA) optical fibers with two arrangements were used in the concrete specimens. One of the LTC groups that had a linear optical fiber arrangement was labeled as ARlin. The other LTC group with bundle optical fiber arrangements was labeled as ARbun. The prepared concrete consisted of cement, fine aggregate, water, mineral additive, acrylic polymer, and superplasticizer. The flexural strengths of LTC with PMMA optical fibers placed longitudinally or laterally were determined. The compressive strengths of LTC specimens with different arrangements were compared. Accelerated aging effects under wetting-drying, freezing-thawing, and high temperature were applied to the ARlin group to investigate these effects on the mechanical properties of LTC. The results of the experiments indicate that the optical fiber arrangements affect the flexural strength, compressive strength, and light transmittance of LTC. The light transmittance increases with the optical fiber content. It is also seen that the flexural strengths and light transmittance of LTC specimens decrease significantly after the high-temperature effect. According to the test results, it is also concluded that LTC with 0.5-mm-diameter optical fibers in a linear arrangement can be used as a construction material under external conditions.

Keywords

light-transmitting concrete, plastic optical fibers, mechanical properties, durability, accelerated aging

Introduction

The term light-transmitting concrete (LTC) or translucent concrete represents a semitransparent material that transmits light with optical fibers or transparent materials in concrete. Many attempts have been made to produce this concrete with its new appearance. LTC has been produced by many companies all over the world.[1] LTC material has the following characteristics: excellent light-transmitting properties, good mechanical properties, light weight, and versatile decorative effects.[2] However, LTC is a high-cost material due to the required workmanship and the complexity of the production process.

Hungarian architect Aron Losonczi invented LTC in 2001 and established a company that produced the world's first commercially available transparent concrete, a combination of optical fibers and concrete. It can be produced as prefabricated blocks.[3] There is a diverse range of applications in which LTC can be implemented, such as floors, facades, pavements, cladding, staircases, partition walls, and others.[4]

LTC enables light to be transmitted through optical fibers in concrete, improves visibility, and reduces energy consumption in a building. Past research works had proven that LTC can transmit light and can reduce light energy consumption by up to 50 % without compromising its compressive strength.[5] Generally, the optical fiber content by volume in LTC is 2.5–5 % for effective light transmission. It is reported that LTC with optical fiber of more than 4 % will reduce its compressive strength drastically and affect its structural performance.[4]

There are several examples in buildings with using LTC. One of the important buildings in LTC applications is the Italian Pavilion in the Shanghai 2010 EXPO. A total of 4,000 LTC blocks were used, and each of the blocks was 100 by 50 by 5 cm in this construction.[6] Instead of optical fibers, plastic resins (polymer-based material) were added to the mortar to produce LTC blocks that covered the facade of the building. The El-Aziz Mosque in Abu Dhabi is another building constructed in 2015 using LTC panels of 30-mm thickness.[7] The European Gate in Hungary, partitions and walls in the Bank of Georgia, and translucent facades in Aachen University were built with LTC.[8]

Several parameters were investigated in previous experimental research on LTC by Bashbash et al., in which they focused on the compressive and flexural strengths of LTC blocks with different optical fiber ratios and diameters. It is reported that compressive strength decreases until fiber content increases, and weight is decreased in concrete with fiber.[9]

Navabi et al. investigated the light transmittance and mechanical properties of LTC using five optical fiber contents (3, 5, 7, 10, and 15 %). The test results showed that the amount of light passing through the LTC did not necessarily match the amount of light falling on them. The maximum light transmittance of the LTC sample was 8.21 %, which corresponded to the sample containing 15 % volumetric optical fiber. Moreover, the minimum light transmittance of the LTC sample was 2.09 %, which corresponded to the sample containing 3 % volumetric optical fiber.[10] Navabi et al. inferred that one of the reasons for that result would be the method of making and cutting optical fibers.

Plastic optical fibers (POFs) were used by Sangeetha et al. to investigate the strength, light-transmittance characteristics, and water permeability of LTC.[11] Also, the light transmission values of LTC changed according to the diameter of optical fibers and the spacing between the fibers. When the spacing between the fibers was decreased, it caused an increase in the light transmission of LTC. In this study, it was also recommended to investigate the durability properties of LTC under external conditions. They stated that the compressive strength depends on the volumetric ratio and diameter of POFs. The compressive strength of the specimens was increased due to the addition of optical fibers. However, other research conducted by Lian and Yin showed that the compressive strength of LTC rose first and then declined with an increase in the volumetric ratio of POF in the specimens.[12] Bashbash et al.,[9] Elgheznawy and Eltarabily,[13] Li, Li, and Guo,[14] Henriques, Dal Molin, and Masuero,[15] and Shahmir and Tantray[16] reported that the compressive strength was decreased by increasing the ratio of the optical fibers. In a study conducted by Tahwia et al., it was stated that the compressive strength results were inconsistent with the findings of many other previous studies, and they reported that compressive strength was increased with the increase in POF diameters and volume ratios.[17]

Huang and Lu used a normal-weight mortar and lightweight mortar in different mix proportions for LTC specimens and compared the compressive strength, light transmission, and thermal properties of LTC.[18] In research conducted by Tahwia et al.,[1] Huang,[6] Shen and Zhou,[19] and Sobo, Farooq, and Azhar,[20] they investigated the light transmission, cost analysis, and energy saving of LTC. Research conducted by Shenoy et al. examined the thermal characterization of LTC in temperature ranges between 50°C and 51°C.[21] Other research by Su et al. focused on the analysis of the dynamic optical transmittance and thermal performance of LTC walls for improved building energy-saving potential.[22]

It is also stated by Chiew et al. that a comprehensive investigation of the durability of LTC was also required to ensure LTC is a durable and sustainable material to use in the construction industry.[5]

After many different types of research in the literature were examined, it was concluded that there has been no comprehensive study on the durability of LTC.[5,6,11] It is considered that this article can be conducive to comprehending the durability performance of LTC in terms of mechanical properties. Also, in a lot of studies,[1,6,9–22] it was seen that the production of LTC was done using linear POF arrangements, and in fact, there were very few studies[23] focusing on different POF patterns in detail. Due to the lack of information about LTC in the literature regarding the suitability of external conditions and different POF arrangements, this research aimed to contribute to the literature by emphasizing the impact of these factors on LTC performance.

The objective of the research presented in this article is to investigate the mechanical properties of LTC according to different optical fiber arrangements and optical fiber content percentages. In addition, accelerated aging effects under wetting-drying, freezing-thawing, and high temperature were applied to investigate these effects on the mechanical properties of LTC. This paper presents and compares the results of light-transmitting performance, compressive strength, and flexural strength of LTC. According to the test results, it is concluded that LTC produced with optical fibers of 0.5 mm in diameter for linear arrangements can be used as a construction material under external conditions.[24]

Materials and Methods

MATERIALS

In this study, cement, fine aggregates, water, superplasticizer, mineral admixtures, and optical fibers were used for the preparation of LTC specimens.

Portland calcareous cement (CEM II/B-L 42.5 R), white, is used in the concrete mix. The cement complies with the requirements in TS EN 197-1, *Cement – Part 1: Composition, Specification and Conformity Criteria for Common Cements*.[25] The physical properties of the cement regarding specific weight, specific surface area, initial and final settings, water percentage, whiteness percentage, volume consistency, and mechanical properties of the cement concerning its compressive strengths for 2, 7, and 28 d are given in **Table 1**.

Chemical properties of the cement concerning its percentage values for insoluble residue, silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron(III) oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), loss on ignition, sulfur trioxide (SO_3), sodium oxide (Na_2O), potassium oxide (K_2O), chloride (Cl^-), and free CaO can be seen in **Table 2**.

As fine aggregates, silica sand was used in this research. The physical characteristics of fine aggregates after the sieve analysis are summarized in **Table 3**. The particle size distribution of sand was continuous grading of 0.12–0.7 mm. The grain/average fineness number of the sand was 44.

For the mineral admixture in the production of the concrete, metakaolin was used as 4.14 % by weight of the cement. The chemical properties of metakaolin are given in **Table 4**.

For chemical admixtures, a polycarboxylate ether-based superplasticizer and acrylic-based polymer were used in the production of mortar. The superplasticizer has the appearance of a light brown liquid. The advantages

TABLE 1

Physical and mechanical properties of the cement[32]

Physical and Mechanical Properties	Units	Values	Requirements, TS EN 197-1	
			Minimum	Maximum
Specific weight	g/cm^3	3.00	…	…
Specific surface area	cm^2/g	5,500	…	…
Initial setting	min	120	60	…
Final setting	min	145	…	…
Water	%	28.6	…	…
Whiteness (Y value as per CIE system)	%	86.5	…	…
Volume consistency (Le Chatelier)	mm	1	…	10
Residue in 0.045 mm sieve	%	1.2	…	…
Residue in 0.090 mm sieve	%	0.1	…	…
Compressive strength (2 d)	MPa	28.0	20	…
Compressive strength (7 d)	MPa	41.2	…	…
Compressive strength (28 d)	MPa	49.0	42.5	62.5

Note: CIE: Commission Internationale de l'Eclairage.

TABLE 2

Chemical properties of the cement[32]

Chemical Properties	Values, %	Chemical Properties	Values, %
Insoluble residue	0.12	SO_3	2.60
SiO_2	17.50	Loss on ignition	11.20
Al_2O_3	3.30	Na_2O	0.25
Fe_2O_3	0.21	K_2O	0.27
CaO	63.50	Chloride (Cl^-)	0.008
MgO	1.15	Free CaO	1.40

TABLE 3

Physical characteristics of fine aggregates

Grain Size, mm	Retained, g	Retained (%) by Weight	Multiplier (for Grain Fineness Number)	Multiplication
1.400	0.000	0.000	6	0.000
1.000	0.000	0.000	9	0.000
0.710	0.060	0.118	15	1.775
0.500	3.740	7.377	25	184.418
0.355	14.320	28.245	35	988.560
0.250	22.210	43.807	45	1,971.302
0.180	9.360	18.462	60	1,107.692
0.125	1.010	1.992	81	161.361
0.090	0.000	0.000	118	0.000
0.063	0.000	0.000	164	0.000
Pan	0.000	0.000	275	0.000
Total	50.700	100.000	…	4,415.108

of using a superplasticizer are to ensure high compressive strength with a low water/cement ratio and good fluidity. The physical characteristics of the superplasticizer are shown in **Table 5**.

The polymer used in this study was an acrylic dispersion-based material that is used in cement-based plaster to improve the quality of mortars by means of adherence and impermeability. The physical characteristics of the polymer can be seen in **Table 6**.

TABLE 4

Chemical properties of the metakaolin

Chemical Properties	Values, %	Chemical Properties	Values, %
SiO_2	59.78	SO_3	1.25
Al_2O_3	10.23	P_2O_5	0.04
Fe_2O_3	0.44	TiO_2	0.15
CaO	9.91	Cr_2O_3	0.0186
MgO	1.59	Mn_2O_3	0.0077
K_2O	0.90	Loss on ignition	16.24
Na_2O	0.05		

TABLE 5

Physical characteristics of the superplasticizer

Physical Properties	
Appearance	Light brown liquid
Odor	Mild
Total solid content, %	55 % (w/w)
pH (undiluted)	2.5
Specific gravity	1.11 (25°C)
Viscosity, Brookfield viscometer, cps	500 (25°C)

TABLE 6

Physical characteristics of the acrylic polymer[33]

Physical Properties	
Color	White
Solid ratio	44 %
Density	1,100 kg/m^3
Application base temperature	+5°C to +35°C
Service temperature	−20°C to +80°C

POFs with a diameter of 0.5 mm were utilized for the production of the specimens. The fiber core material was made of polymethyl methacrylate resin. The properties of the optical fibers concerning structural and mechanical characteristics as well as optical and heat performance are given in **Table 7**.

PREPARATION OF THE SPECIMENS

In this study, the mix design was used for making the LTC specimens. The grain size of the fine aggregate used in the specimens was chosen to be smaller than 1 mm because of the narrow distances between the optical fibers. To determine the effects on the properties of LTC in terms of optical fiber arrangement, optical fibers were placed differently in the molds. The sample groups with two different patterns of optical fibers were named ARlin and ARbun. The ARlin group had a linear optical fiber pattern, whereas the ARbun group had a bundle (quad optical fiber group) pattern. In this manner, three different optical fiber content percentages (by volume) were used: 1.0, 1.6, and 2.4 %. To compare ARlin and ARbun specimens, a reference group named REF was produced without optical fibers. To determine the effect on the properties of LTC in terms of optical fiber direction, optical fibers were placed in the long or short direction. For the ARlin group, the samples that included 1.0 % optical fiber in the long direction were named ARlin-1.0-L. For the ARlin group, the specimens that had 1.0 % optical fiber content in the short direction were named ARlin-1.0-S. That labeling was similar for the ARbun group. The names of the

TABLE 7
The properties of the 0.5 mm POFs[34]

Properties of Φ 0.5 mm Plastic Optical Fibers		
Structural characteristic	Fiber core material	Polymethyl methacrylate resin
	Cladding material	Fluorinated polymer
	Core refractive index	1.49
	Refractive index profile	Step index
	Numerical aperture	0.5
	Core diameter	485 µm
	Overall diameter	500 µm
	Approximate weight, g/m	0.24
Mechanical characteristic	Minimum bend radius	Minimum 10 mm
	Tensile strength	Minimum 14 N
Optical properties	Transmission loss (650 nm collimated light)	Maximum 250 (dB/km)
Heat performance	Storage and operation temperature	−55°C to +70°C
	Operating temperature in a moist atmosphere	Maximum 60°C

TABLE 8
The labeling of LTC specimens

Φ 0.5 mm POF		ARlin (Linear Pattern)			ARbun (Bundle Pattern)			REF (without POF)
POF content by volume, %		1.0	1.6	2.4	1.0	1.6	2.4	0
POF direction	Long	ARlin-1.0-L	ARlin-1.6-L	ARlin-2.4-L	ARbun-1.0-L	ARbun-1.6-L	ARbun-2.4-L	REF
	Short	ARlin-1.0-S	ARlin-1.6-S	ARlin-2.4-S	ARbun-1.0-S	ARbun-1.6-S	ARbun-2.4-S	

specimens changed according to the fibers' pattern arrangement, content percentage by volume, and direction. All produced specimens' names of LTC are given in **Table 8**.

The production method of the specimens in this study was prepared by using steel wires attached to metal frames for arranging optical fibers in the desired patterns. The metal frames were fixed to the wooden formwork with steel bolts and steel screws. The views of the completed formwork are shown in **figure 1*A*** and **1*B***.

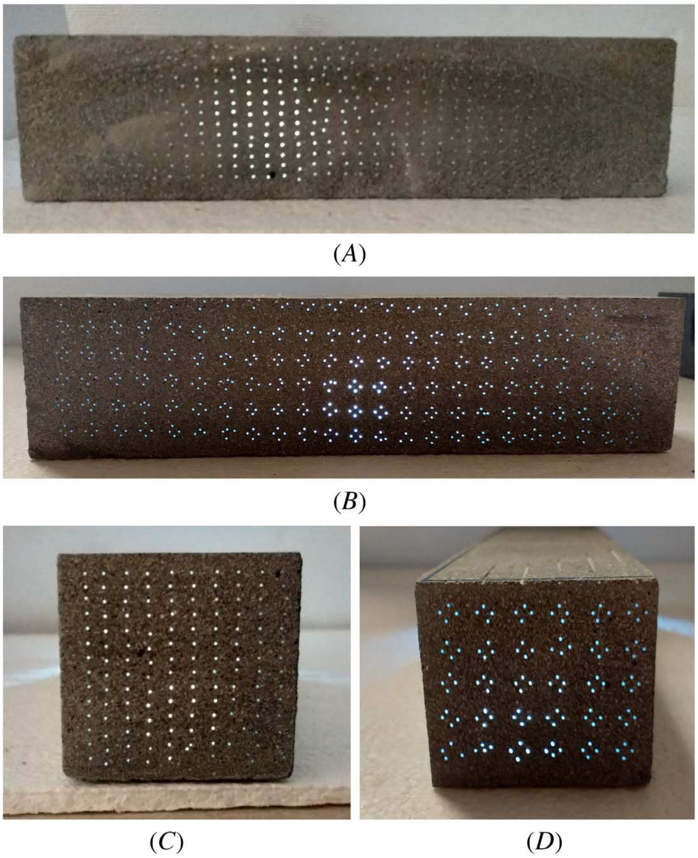
Three prismatic specimens with dimensions of 40 by 40 by 160 mm were produced for each group of ARlin and ARbun of different patterns with different optical fiber contents (1.0, 1.6, and 2.4 %). After the preparation of the formworks, the molds were filled with fresh concrete. The specimens were cured under laboratory conditions

FIG. 1 The views of completed formwork. (*A*) Top view of the completed formwork. (*B*) The view of the metal frame with fibers.


(*A*) (*B*)

FIG. 2

Final shapes of LTC specimens. (*A*) The view of ARlin-1.6-S specimen. (*B*) The view of ARbun-1.6-S specimen. (*C*) The view of ARlin-1.6-L specimen. (*D*) The view of ARbun-1.6-L specimen.


(*A*)
(*B*)
(*C*)
(*D*)

for 28 d before testing. The hardened LTC blocks were cut into smaller prisms of 40-mm thickness. Some exemplar photos for the final shapes of LTC specimens can be seen in **figure 2*A*–*D***.

Test Methods

TESTING OF FLEXURAL STRENGTHS

The flexural strength tests of LTC specimens were carried out following EN 12390-5, *Testing Hardened Concrete – Part 5: Flexural Strength of Test Specimens.*[26] The loading rate applied was 0.05 MPa/s. To calculate the flexural strengths of LTC specimens, the distribution of the optical fibers was chosen perpendicular to the direction of the force.[2] The images demonstrating failure modes of LTC specimens after the testing procedure are given in **figure 3**.

TESTING OF COMPRESSIVE STRENGTHS

The compressive strength tests of LTC specimens were carried out following EN 12390-3, *Testing Hardened Concrete – Part 3: Compressive Strength of Test Specimens.*[27] The compression area of the specimens was 40 by 40 mm. The compressive force was applied perpendicular to the arrangement distribution of the optical fibers. The applied compressive loading rate was 2.4 kN/s for all specimens. The image demonstrating the failure mode of LTC specimens after the testing procedure is given in **figure 4**. The number of specimens for each setup is shown in **Table 9**.

FIG. 3 Flexural strength tests for ARlin specimens.

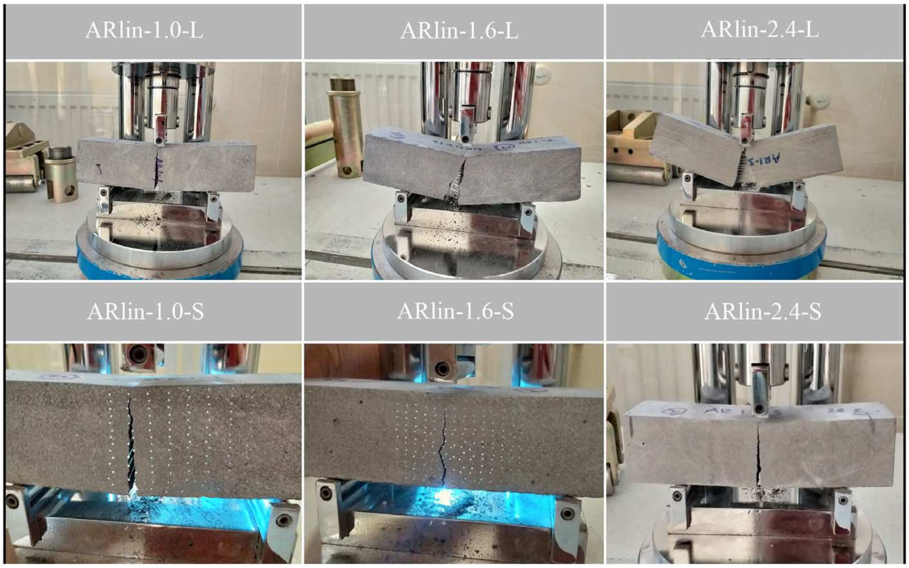
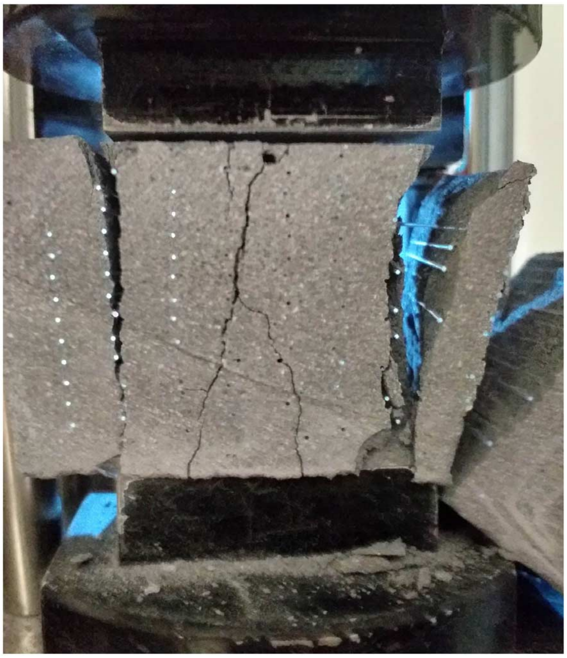


FIG. 4

Compressive strength test of the specimen (ARlin-1.0-S).



TESTING OF LIGHT TRANSMITTANCE

A test setup was produced for the light-transmittance tests of the specimens (**fig. 5**). The light transmittance is a ratio that is the luminous flux transmitted from the component over the luminous flux falling on the component.[1] The light transmittance of the specimens is measured by a lux meter. The dimensions of the test setup were 190 by 200 by 550 mm.

TABLE 9

The number of test specimens for flexural and compression tests

Test Conditions Laboratory Conditions (23°C ± 2°C, 50 % Relative Humidity)	Number of Flexural Test Specimens (L)[a]	Number of Flexural Test Specimens (S)[a]	Number of Compression Test Specimens (S)[b]
ARlin-1.0-S/L	3	3	6
ARlin-1.6-S/L	3	3	6
ARlin-2.4-S/L	3	3	6
ARbun-1.0-S/L	3	3	6
ARbun-1.6-S/L	3	3	6
ARbun-2.4-S/L	3	3	6

Note: [a] The flexural tests were applied to specimens that had POF in the long axis (L) and short axis (S). [b] The compression tests were only applied to specimens that had POF in the short axis (S).

FIG. 5

Light-transmittance test setup.

The measurements were done by placing specimens between the light source and the lux meter. Three cubic specimens with dimensions of 40 by 40 by 40 mm were produced for each LTC group.

The light transmittance was measured at distances of 100 and 200 mm. To determine the light-transmittance values, the formula specified in equation (1) of ISO 13468-1:2019, *Plastics – Determination of the Total Light Transmittance of Transparent Materials*, was used.[27]

$$\tau_t = \frac{\tau_2}{\tau_1} \times 100 \tag{1}$$

where τ_t is the total light transmittance (%), τ_2 is the amount of light transmittance through the sample, and τ_1 is the amount of light transmittance when there is no sample.

ACCELERATED AGING TESTS

The accelerated aging tests were observed only for the ARlin group specimens under wetting-drying, freezing-thawing, and high temperature. The number of specimens subjected to flexural and compression tests after accelerated aging effects are shown in **Table 10**.

TABLE 10
The number of test specimens subjected to flexural and compression tests after accelerated aging effects

Specimens	Test Conditions	Number of Flexural Test Specimens (L)[a]	Number of Flexural Test Specimens (S)[b]	Number of Compression Test Specimens (S)[b]
ARlin-1.0-S/	Wetting-drying	3	3	6
LARlin-1.6-S/	Freezing-thawing	3	3	6
LARlin-2.4-S/L	High temperature	3	3	6

Note: [a] The flexural tests were applied to specimens that had POF in the long axis (L) and short axis (S). [b] The compression tests were only applied to specimens that had POF in the short axis (S).

Wetting-Drying Effect

To determine the durability performance of LTC specimens (ARlin) under accelerated aging, wetting-drying cycles were carried out following EN 12467:2012+A2:2018, *Fibre-Cement Flat Sheets – Product Specification and Test Methods*.[29] For the wetting-drying tests, LTC test specimens were immersed in 20°C water for 18 h and then dried at 60°C ± 5°C for 6 h at each cycle. Fifty cycles were completed during the test procedure. After performing wetting-drying cycles, ARlin group specimens are subjected to flexural and compressive tests.

Freezing-Thawing Effect

To determine the durability performance of LTC specimens (ARlin), freezing-thawing cycles were carried out following EN 12467:2012+A2:2018.[29] A full automatic freezing-thawing chamber was used for the test procedure. Following the standard, each freezing-thawing cycle was performed by freezing test specimens for 1–2 h at −20°C ± 4°C while holding this temperature constant for a further hour, then thawing them in water for 1–2 h at 20°C ± 4°C while again holding this temperature constant for a further hour. One hundred cycles were completed during the test procedure. After performing freezing-thawing cycles, flexural and compressive tests were carried out for ARlin group specimens.

High-Temperature Effect

LTC test specimens (ARlin) were also tested to determine their behavior in high temperature according to ISO 1182:2020, *Reaction to Fire Tests for Building Products – Non-combustibility Test*.[30] The proprietary specifications provided by the manufacturer indicate the temperature resistance of the POFs to be 70°C. For the test procedure, the ARlin group specimens were exposed to 150°C temperature in the ventilated oven for 1 h. The working temperature of the ventilated oven was between +5°C and +250°C. After the procedure, the concrete and optical fiber surfaces were controlled for any possible visual damage. After the high-temperature effect, flexural and compressive tests were also performed. The weight of the specimens was also measured before and after the high-temperature effect.

Results and Discussion

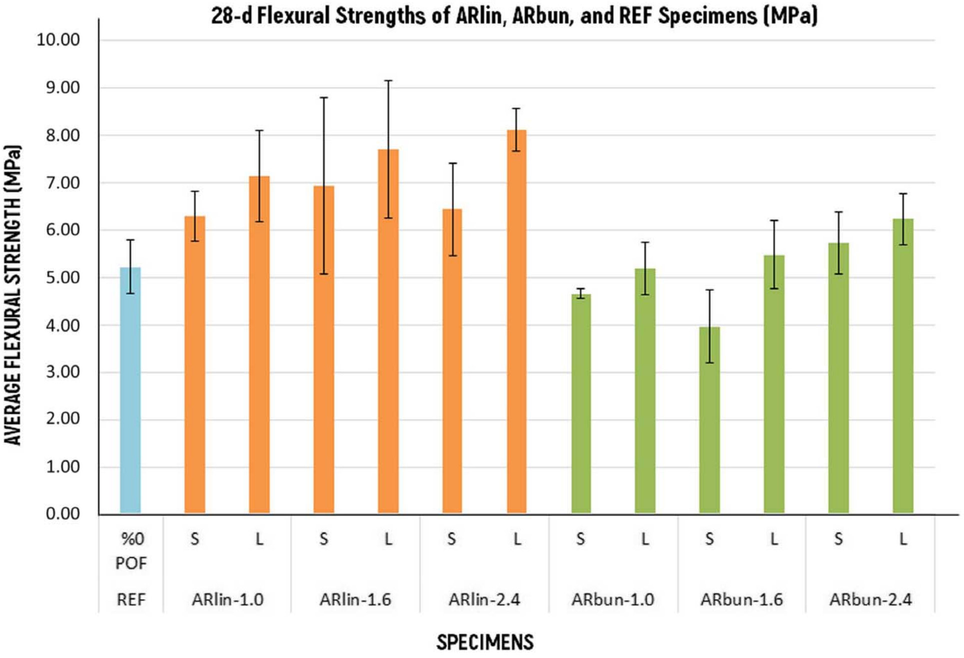
FLEXURAL TEST RESULTS

The test results for 28-d flexural strengths and the standard deviation of LTC specimens with respect to their POF content and arrangements are given in **Table 11**. The comparison of the results is shown in **figure 6**. The results of flexural strength tests show that by using optical fibers in the longitudinal way, the flexural strength of the LTC specimens was slightly increased. It was also seen that linear POF arrangement increases the flexural strengths of

TABLE 11
Results of 28-d flexural tests

POF Content, %	Specimen Names	28-d Average Flexural Strength, MPa	Standard Deviation, MPa
0	REF	5.22	0.57
1.0	ARlin-1.0-S	6.29	0.52
1.6	ARlin-1.6-S	6.93	1.86
2.4	ARlin-2.4-S	6.44	0.98
1.0	ARlin-1.0-L	7.13	0.96
1.6	ARlin-1.6-L	7.70	1.46
2.4	ARlin-2.4-L	8.11	0.44
1.0	ARbun-1.0-S	4.66	0.10
1.6	ARbun-1.6-S	3.96	0.76
2.4	ARbun-2.4-S	5.72	0.65
1.0	ARbun-1.0-L	5.19	0.55
1.6	ARbun-1.6-L	5.47	0.72
2.4	ARbun-2.4-L	6.23	0.53

FIG. 6 The 28-d flexural strength test results of LTC specimens.



LTC specimens. However, by increasing the percentage content of the optical fibers by volume in the specimens with the linear arrangement, the flexural strength was slightly increased.

The analysis of variance (ANOVA; one-way) test results of the flexural strengths for the specimens with and without POF according to POF content are given in Table 12. The statistical results show that the POF content is not significant for the flexural strength values of the specimens. However, in the research by Henriques et al., the ANOVA results showed that the addition of POFs is significant and decreased the flexural tensile strength of the LTC.[15] It can be concluded in this research that one reason for this result may be the use of small POF percentages instead of larger ones.

TABLE 12

The ANOVA (one-way) test results of the flexural strength of the specimens with and without POF at Day 28 according to POF content

Groups		SS	DF	MS	*F*	Probability	Comment
ARlin-S	Between groups	4.64	3	1.55	0.82	0.52	NS
	Within groups	15.10	8	1.89	…	…	…
	Total	19.74	11	…	…	…	…
ARlin-L	Between groups	14.70	3	4.90	3.66	0.06	NS
	Within groups	10.71	8	1.34	…	…	…
	Total	25.41	11	…	…	…	…
ARbun-S	Between groups	5.14	3	1.71	3.44	0.07	NS
	Within groups	3.99	8	0.50	…	…	…
	Total	9.13	11	…	…	…	…
ARbun-L	Between groups	2.11	3	0.70	1.32	0.33	NS
	Within groups	4.26	8	0.53	…	…	…
	Total	6.37	11	…	…	…	…

Note: SS = sum of square; DF = degrees of freedom; MS = mean sum of squares; *F* = test statistic; probability = *p* value, significance level of 5 %; comment = NS, nonsignificant effect.

The *t*-test results of the flexural strength for the specimens according to POF arrangement are given in **Table 13**. It is concluded that POF arrangement was found to be significant for the flexural strength in most of the LTC specimens.

Initially, LTC specimens that had POF in the long axis (shown with L in the labeling) were expected to be more resistant to the flexural effects, but the test results showed that the flexural strength values are close to the values of LTC specimens having POF in the short axis (shown with S in the labeling). The reason for this result can be the lack of adherence between the POFs and the concrete due to the smooth surface of POF.

In addition, ARlin group specimens had higher flexural strength values than the ARbun group specimens. One of the reasons for this result can be POF spacing differences between these two groups of specimens. POF spacings were 1.5 mm for ARbun and 2.3 mm for ARlin groups. The flexural strengths were decreased in the ARbun group because the minimum POF spacing was increased. It can be deduced that the POF worked as reinforcements in the ARlin group because of the higher values in the flexural strength for both (S and L) directions.

COMPRESSION TEST RESULTS

The 28-d compressive strengths of LTC specimens and standard deviation of the test results are given in **Table 14**. The reference specimens without POF had the highest average compressive strength value of 54.98 MPa. The test results are compared in **figure 7**. It is seen that the compressive strengths of the LTC specimens were decreased by

TABLE 13

The *t*-test results of the flexural strength of the specimens with POF at Day 28 according to POF arrangement (linear or bundle)

Groups		*t*-Test	*t*	DF	MD	SED	Probability	Comment
S	1 % POF	Equal variances assumed	4.37	4	1.63	0.37	0.006	S
	1.6 % POF	Equal variances assumed	2.08	4	2.96	1.42	0.05	S
	2.4 % POF	Equal variances assumed	0.85	4	0.71	0.83	0.22	NS
L	1 % POF	Equal variances assumed	2.48	4	1.94	0.78	0.03	S
	1.6 % POF	Equal variances assumed	1.94	4	2.34	1.15	0.06	NS
	2.4 % POF	Equal variances assumed	3.87	4	1.88	0.49	0.009	S

Note: *t* = computed test statistics; DF = degrees of freedom; MD = mean difference; SED = standard error difference; probability = *p* value (one sided), significance level of 5 %; comment = S, significant effect and NS, nonsignificant effect.

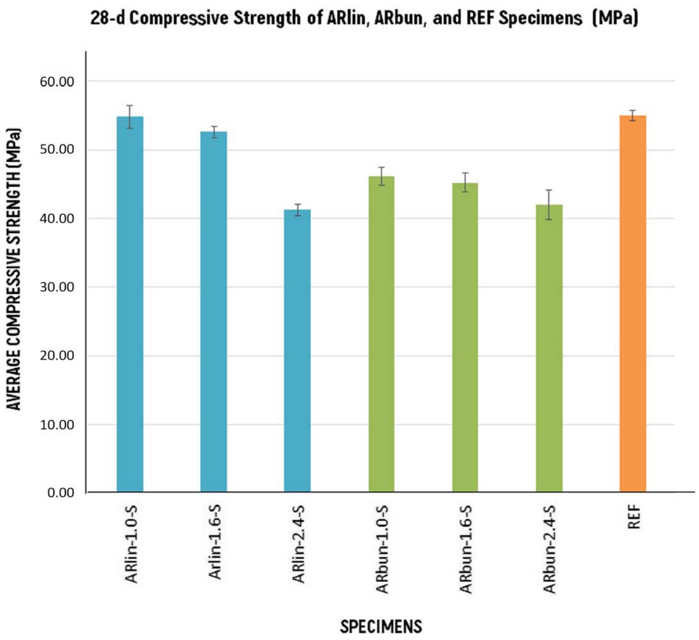
TABLE 14

Results of 28-d compression tests

POF Content, %	Specimen Name	28-d Average Compressive Strength, MPa	Standard Deviation, MPa
0	REF	54.98	0.78
1.0	ARlin-1.0-S	54.79	1.70
1.6	ARlin-1.6-S	52.29	0.85
2.4	ARlin-2.4-S	41.24	0.84
1.0	ARbun-1.0-S	46.16	1.29
1.6	ARbun-1.6-S	45.24	1.38
2.4	ARbun-2.4-S	42.04	2.14

FIG. 7

The 28-d average compressive strengths of LTC specimens.



the increase in the POF content. The ANOVA (one-way) test results of the compressive strength of the specimens with and without POF at Day 28 according to POF content are given in Table 15. The ANOVA test results also show that there is a significant difference between the compressive strengths according to POF content. Using the

TABLE 15

The ANOVA (one-way) test results of the compressive strength of the specimens with and Without POF at Day 28 according to POF content

Groups		SS	DF	MS	*F*	Probability	Comment
ARlin	Between groups	761.47	3	253.82	172.12	0.000	S
	Within groups	29.49	20	1.47	…	…	…
	Total	790.96	23	…	…	…	…
ARbun	Between groups	552.33	3	184.11	70.04	0.000	S
	Within groups	52.57	20	2.63	…	…	…
	Total	604.90	23	…	…	…	…

Note: SS = sum of square; DF = degrees of freedom; MS = mean sum of squares; *F* = test statistic; probability = *p* value, significance level of 5 %; comment = S, significant effect and NS, nonsignificant effect.

TABLE 16

The *t*-test results of the compressive strength of the specimens at Day 28 according to POF arrangement (linear or bundle)

POF Content	*t*-Test	*t*	DF	MD	SED	Probability	Comment
1 % POF	Equal variances assumed	9.06	10	8.63	0.95	0.000	S
1.6 % POF	Equal variances assumed	7.81	10	6.43	0.82	0.000	S
2.4 % POF	Equal variances assumed	−0.77	10	−0.79	1.03	0.23	NS

Note: t = computed test statistics; DF = degrees of freedom; MD = mean difference; SED = standard error difference; probability = p value (one sided), significance level of 5 %; comment = S, significant effect and NS, nonsignificant effect.

statistical method of Tukey, the compressive strengths of ARlin specimens for 1.6 and 2.4 % POF contents differ significantly from those that include 1.0 and 0 % POF content. Also, there is a significant decrease in the compressive strengths of ARbun specimens with 1.0, 1.6, and 2.4 % POF contents when compared with REF (0 %). One of the reasons for this strength loss can be explained by the increase in POF cross-sectional areas obstructing the homogeneity of the concrete. Henriques et al. indicated that one of the main reasons for the decreasing mechanical strength of LTC with increasing fiber content in the specimens is the fiber/matrix interface.[15] Due to the smooth surface of optical fiber, the transition zone is damaged within the matrix.

The *t*-test results (independent samples) of the compressive strength of the specimens with POF at Day 28 according to POF arrangement are given in **Table 16**. The results showed that containing linear or bundle POF arrangement was significant for compressive strength in the specimens with 1.0 and 1.6 % POF content.

ARlin group specimens, which have linear POF arrangement, had higher compressive strength values than ARbun group specimens. The reason for this increase might be the effect of patterns and the increase of POF spacings in the specimens. The minimum POF spacing was 2.3 mm for ARlin and 1.5 mm for ARbun specimens. Because of the close distance between concrete and POFs, ARbun specimens had lower compressive strength values.

LIGHT-TRANSMITTANCE TEST RESULTS

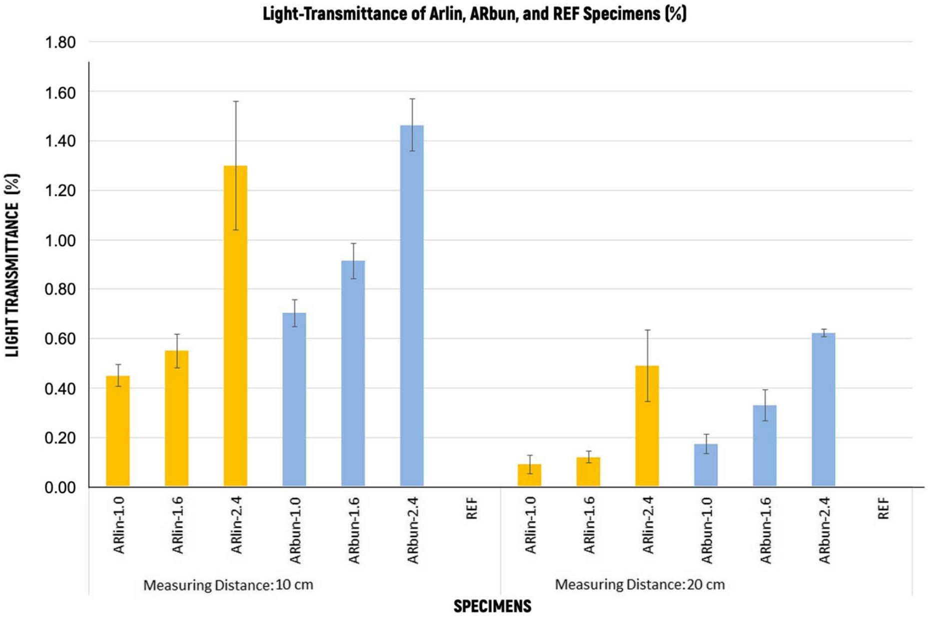
The results of the light-transmittance test are given in **Table 17**. In the bar chart given in **figure 8**, it can be seen that the light-transmittance values of the ARbun specimens are greater than the ARlin specimens. In the 10 cm measuring distance, the light-transmittance values of ARlin specimens are 35, 39, and 10 % less than the ARbun specimens according to the POF content of 1.0, 1.6, and 2.4 %, respectively. In the 20 cm measuring distance, the

TABLE 17

Results of the light transmittance tests

Measuring Distance	POF Content, %	Specimen Name	Light Transmittance, %	Light Transmittance, lux
10 cm	0	REF	0.00	0.00
	1.0	ARlin-1.0-S	0.45	18.04
	1.6	ARlin-1.6-S	0.55	19.53
	2.4	ARlin-2.4-S	1.30	49.31
	1.0	ARbun-1.0-S	0.70	26.71
	1.6	ARbun-1.6-S	0.91	34.73
	2.4	ARbun-2.4-S	1.46	55.66
20 cm	0	REF	0.00	0.00
	1.0	ARlin-1.0-S	0.09	1.31
	1.6	ARlin-1.6-S	0.12	1.53
	2.4	ARlin-2.4-S	0.49	6.62
	1.0	ARbun-1.0-S	0.17	2.34
	1.6	ARbun-1.6-S	0.33	4.48
	2.4	ARbun-2.4-S	0.62	8.42

FIG. 8 The light-transmittance test results for LTC specimens.



light-transmittance values of ARlin specimens are 47, 64, and 21 % less than the ARbun specimens according to the POF content of 1.0, 1.6, and 2.4 %, respectively. The reason for higher values obtained for ARbun specimens can be explained as the result of the optical fibers arrangement, in which the fibers are closer to each other. One of the experimental studies by Thomas and Shivaranjani indicated that as the number of plastic fibers in the LTC specimen increases, its light-transmitting capacity also increases.[31] In the research conducted by Li et al., 1 and 0.5 mm optical fibers were used in the specimens, and when the number of fibers is a certain value, regardless of white or red light, the optical power decreases with an increasing distance from the light source to the specimen.[2] In this research, results similar to previous research were obtained, in which as the POF content in the specimens increases, the light transmittance also increases.

The ARbun specimens with the largest content of POF (2.4 %) had the highest light transmittance. By increasing the distance between the lux meter and the specimen from 10 to 20 cm, the light transmittance decreased by 80, 78, and 62 % for ARlin-1.0, ARlin-1.6, and ARlin-2.4 specimens, respectively. Also, for the ARbun-1.0, ARbun-1.6, and ARbun-2.4 specimens, the light transmittance decreased by 75, 63, and 57 %, respectively.

Also, the ANOVA (one-way) test results of the light transmittance (lux) of the specimens with and without POF according to POF content are given in **Table 18**. The ANOVA test results showed that there was a significant difference between the light-transmittance values according to POF content.

ACCELERATED AGING TEST RESULTS

Results of the Flexural Tests after the Accelerated Aging Effects

The flexural strength tests after the accelerated aging effects for wetting-drying, freezing-thawing, and high temperature are evaluated. The average flexural test results and standard deviation of LTC specimens with respect to their POF content and arrangements are summarized in **Table 19**. The comparison of the results can be seen in **figure 9**.

TABLE 18

The ANOVA (one-way) test results of the light-transmittance (lux) of the specimens according to POF content

Groups		SS	DF	MS	*F*	Probability	Comment
ARlin (10 cm)	Between groups	3,753	3	1,251	12.0	0.002	S
	Within groups	834	8	104.2	…	…	…
	Total	4,587	11	…	…	…	…
ARbun (10 cm)	Between groups	4,849.5	3	1,616	156.6	<0.001	S
	Within groups	82.5	8	10.32	…	…	…
	Total	4,932	11	…	…	…	…
ARlin (20 cm)	Between groups	78.36	3	26.12	16.56	<0.001	S
	Within groups	12.62	8	1.58	…	…	…
	Total	90.98	11	…	…	…	…
ARbun (20 cm)	Between groups	116	3	38.73	100.6	<0.001	S
	Within groups	3.08	8	0.38	…	…	…
	Total	119.08	11	…	…	…	…

Note: SS = sum of square; DF = degrees of freedom; MS = mean sum of squares; *F* = test statistic; probability = *p* value, significance level of 5 %; comment = S, significant effect and NS, nonsignificant effect.

TABLE 19

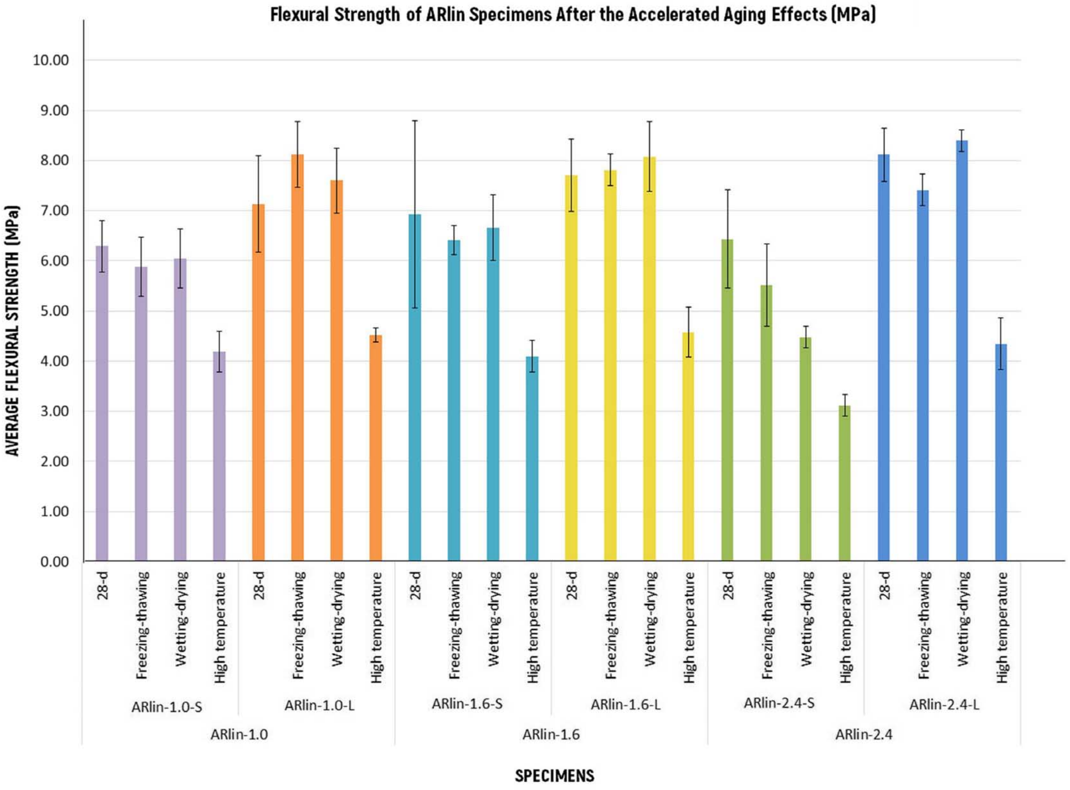
Results of the flexural tests after the accelerated aging effects

Test Conditions	POF Content, %	Specimen Name	Average Flexural Strength, MPa	Standard Deviation, MPa
Wetting-drying	1.0	ARlin-1.0-S	6.05	0.59
	1.6	ARlin-1.6-S	6.66	0.65
	2.4	ARlin-2.4-S	4.48	0.21
	1.0	ARlin-1.0-L	7.60	0.65
	1.6	ARlin-1.6-L	8.08	0.70
	2.4	ARlin-2.4-L	8.40	0.22
Freezing-thawing	1.0	ARlin-1.0-S	5.87	0.59
	1.6	ARlin-1.6-S	6.41	0.29
	2.4	ARlin-2.4-S	5.51	0.82
	1.0	ARlin-1.0-L	8.12	0.65
	1.6	ARlin-1.6-L	7.81	0.32
	2.4	ARlin-2.4-L	7.42	0.31
High temperature	1.0	ARlin-1.0-S	4.18	0.40
	1.6	ARlin-1.6-S	4.09	0.31
	2.4	ARlin-2.4-S	3.12	0.21
	1.0	ARlin-1.0-L	4.51	0.14
	1.6	ARlin-1.6-L	4.57	0.50
	2.4	ARlin-2.4-L	4.34	0.51

After the freezing-thawing effect, the flexural strength of ARlin-1.0-S specimens decreased by 6.68 %. After the wetting-drying effect, the flexural strength of ARlin-1.0-S specimens decreased by 3.82 %. After the high-temperature effect, the flexural strength of ARlin-1.0-S specimens decreased by 33.39 %. After the freezing-thawing effect, the flexural strength of ARlin-1.0-L specimens increased by 13.88 %. After the wetting-drying effect, the flexural strength of ARlin-1.0-L specimens increased by 6.59 %. After the high-temperature effect, the flexural strength of ARlin-1.0-L specimens decreased by 36.75 %.

The flexural strengths of ARlin-1.6-S specimens decreased by 7.50 % after the freeze-thawing effect, by 3.90 % after the wetting-drying effect, and by 40.98 % after the high-temperature effect. The flexural strengths of ARlin-1.6-L specimens increased by 1.43 and 4.94 % after the freeze-thaw effect and wetting-drying effect, respectively, but decreased by 40.65 % after the high-temperature effect.

FIG. 9 The average flexural strength test results of LTC specimens after accelerated aging effects.

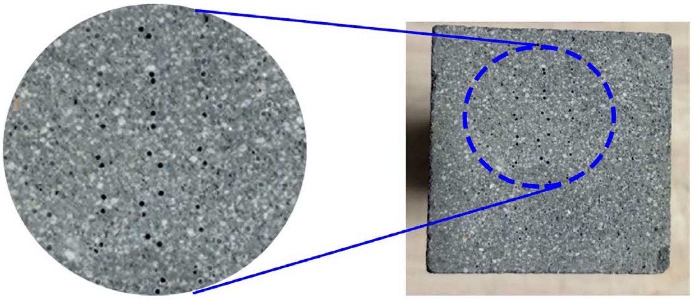


The flexural strength of ARlin-2.4-S specimens decreased by 14.44 % after the freezing-thawing effect, by 30.43 % after the wetting-drying effect, and by 51.55 % after the high-temperature effect. The flexural strength of ARlin-2.4-L specimens increased by 3.58 % after the wetting-drying effect but decreased by 3.58 % after the freezing-thawing effect and decreased by 46.69 % after the high-temperature effect.

These results indicate that the flexural strengths of ARlin-L specimens, which include POF in the long direction, had similar values after the freezing-thawing and wetting-drying effects. The reason for this might be that the LTC includes small-diameter (0.5 mm) optical fibers and small-sized particles (maximum 0.7 mm for sand), therefore providing a high adhesive performance of the interface between the matrix and fibers. Also, in the research by Li et al., 1 and 0.5 mm optical fibers were used in the LTC specimens, and it was concluded that for the flexural tests, the adhesive performance between the matrix and fiber in 0.5 mm fiber was better than the specimens with 1.0-mm diameter.[2] In this research, after wetting-drying and freezing-thawing, it was observed that the flexural strengths of the ARlin-L specimens were bigger than 7 MPa and that these values were close to the value of 28 d. However, the flexural strengths of the ARlin-L specimens decreased by up to 47 % after the high-temperature effect. For the ARlin-S specimens, the greatest decrease in the flexural strength resulted from the effect of high temperature. The reason for these significant decreases can be a result of the melting of POF and the formation of small voids in the concrete with the high-temperature effect (fig. 10). It is concluded that the performance of optical fibers was more effective on the flexural test results. Therefore, the test temperature range for wetting-drying cycles was between +20°C and +60°C, and for freezing-thawing cycles, the range was between −20°C and +20°C. However, the optical fiber is a waterproof material, and the operating temperature of POF is between −55°C and +70°C. For this reason, it can be concluded that high temperature has a crucial effect on POF in the LTC specimens.

FIG. 10

Melted POFs in the specimen (ARlin-L) after the high-temperature effect.



Results of the Compression Tests after the Accelerated Aging Effects

The compressive strength tests were performed after the accelerated aging effects of wetting-drying, freezing-thawing, and high temperature. The standard deviations of LTC specimens with respect to their POF contents and arrangements are summarized in Table 20.

The comparison of the results can be seen in figure 11. These results indicate that the compressive strength of ARlin specimens slightly decreased after the accelerated aging effects.

When compared with the results of 28-d compressive test for the ARlin-1.0-S specimens, it was seen that there was a 28.93 % decrease in the average compressive strength of the specimens after the freezing-thawing effect, 11.92 % decrease after the wetting-drying effect, and 12.21 % decrease due to the high-temperature effect. When compared with the result of the 28-d compressive test for the ARlin-1.6-S specimens, after the freezing-thawing, wetting-drying, and high temperature accelerated aging effects, it was found that there were 10.25, 2.85, and 10.48 % decreases in the average compressive strengths of the specimens, respectively. When compared with the result of the 28-d compressive test for the ARlin-2.4-S specimens, due to the freezing-thawing, wetting-drying, and high-temperature effects, it was found that there were 4.32, 7.93, and 8.78 % decreases in the average compressive strengths of the specimens, respectively.

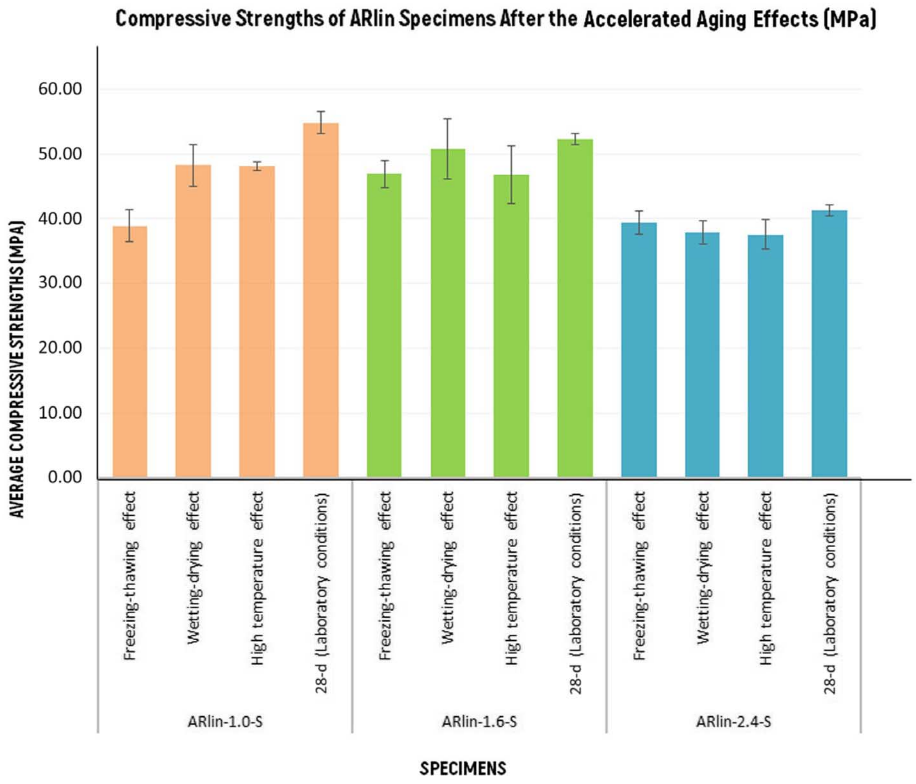
The compressive strength of the ARlin specimens decreased between 4 and 29 % after the freezing-thawing effect, 2 and 12 % after the wetting-drying effect, and 8 and 12 % after the high-temperature effect. It is concluded from the results that the compressive strength of LTC slightly decreased after the accelerated aging factors. For the compressive strengths of the specimens exposed to high temperature (which was greater than 37 MPa), there was no significant difference between the 28-d results. A considerable change in compressive strengths was only present in ARlin-1.0 specimens after the freezing-thawing. However, the differences were inconsistent for the other specimens (ARlin-1.6 and ARlin-2.4). The reason for this may be that concrete can be more affected than

TABLE 20

Results of the compression tests after the accelerated aging effects

Test Conditions	POF Content, %	Specimen Name	Average Compressive Strength, MPa	Standard Deviation, MPa
Wetting-drying	1.0	ARlin-1.0-S	48.26	3.16
	1.6	ARlin-1.6-S	50.80	4.59
	2.4	ARlin-2.4-S	37.97	1.77
Freezing-thawing	1.0	ARlin-1.0-S	37.98	2.42
	1.6	ARlin-1.6-S	46.93	2.15
	2.4	ARlin-2.4-S	39.46	1.83
High temperature	1.0	ARlin-1.0-S	48.10	0.72
	1.6	ARlin-1.6-S	46.81	4.43
	2.4	ARlin-2.4-S	37.62	2.27

FIG. 11 The compressive strength test results of LTC specimens after accelerated aging effects.



optical fibers under freezing-thawing and wetting-drying and that the compressive strengths of LTC were determined by the concrete part that was affected strongly by these agents.

Conclusions

LTC is an innovative building material that can be used in a wide variety of areas in construction technology. Based on the results of the experimental tests, the following conclusions can be drawn:

1. It can be concluded that the direction and patterns of POFs affect the flexural strengths of LTC specimens. Also, POF content and POF arrangement are significant parameters for the compressive strength of LTC.
2. The flexural strengths of LTC specimens increased with the linear POF arrangement (ARlin) in the concrete. It is concluded that the POF spacing in a pattern is a substantial parameter for the strengths of LTC.
3. The light transmittance decreased with the increase of the measuring distance between the lux meter and specimens.
4. After accelerated aging effects on the LTC test specimens were performed, it was observed that there was a significant decrease in flexural strength after high temperature, and it is also seen that the compressive strength decreased up to 29 % after freezing-thawing. It was concluded that high temperature and freezing-thawing are important parameters affecting the mechanical strengths of LTC.

RECOMMENDATION

It is recommended to investigate the durability properties of LTC by increasing the number of test specimens and also by producing larger-sized blocks. Because labor is expensive and the cost of optical fibers is high, future researchers are expected to focus on improving products with low-cost light-transmitting materials to be competitive in the construction industry.

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