



Effect of polymer content and temperature on mechanical properties of lightweight polymer concrete

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HIGHLIGHTS

- Lightweight polymer concrete (LWPC) is studied as a material of high strength-to-weight ratio.
- Mechanical properties of LWPCs tested at different temperatures are obtained.
- Optimum conditions to develop desirable material properties are identified.
- Statistical analyses are conducted to understand the influence of each parameter on mechanical properties of LWPC.

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ABSTRACT

This study investigates the mechanical properties of lightweight polymer concrete (LWPC) containing four different polymer ratios (10%, 12%, 14%, and 16%) tested at three different temperatures (-15°C , $+5^{\circ}\text{C}$, and $+25^{\circ}\text{C}$) using destructive and non-destructive tests. In addition, a series of expressions are suggested to predict the splitting-tensile, flexural and impact strength of LWPC based on the main parameters and compressive strength. The analysis of variance (ANOVA) method was also used to determine relative contributions of the experimental parameters. The results of the destructive tests show that increasing the polymer ratio caused an increase in the compressive, splitting-tensile, and impact strengths, and energy absorption of LWPC. With decreasing the temperature from $+25^{\circ}\text{C}$ to -15°C , the compressive, splitting-tensile, flexural strengths, and elastic modulus (EM) increased, whereas the energy absorption, impact energy, and ductility decreased. The findings of this research provide beneficial information toward understanding the behavior of LWPC and its safe use in engineering applications where a material of high strength-to-weight ratio is required.

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1. Introduction

Over the last decades, finding novel efficient, cost-effective, and eco-friendly solutions on the development of new infrastructures has become of prime importance [1,2]. The requirement of having energy efficient buildings necessitates the development of new materials and improvement of existing materials and lightweight structures [3–5]. Weight reduction is a key factor in the development of materials and components to use in many structural and construction practices such as bridge components, parking structures, piers, and beams. Lightweight concretes (LWC) are widely used for such purposes. However, design of these structures presents challenges, as they need to be light whilst being safe, durable and easy to maintain [6,7].

Due to the primary characteristics of LWC (i.e., adequate compressive strength, acceptable durability, low density and improved properties of thermal conductivity) its applications in structural applications allow the use of smaller size foundations and beam and column cross-sections. Likewise, the use of LWC in place of conventional concrete reduces the structural dead load, which leads to a reduction in seismic forces [8,9]. Structural LWC also benefits from energy savings, as it possesses improved thermal conductivity [10–12] and sound insulation properties [13–16]. Other advantages of using LWC in structures are the ease of transportation and handling of precast units on site, leading to faster construction [17].

LWC with natural lightweight or artificially calcined aggregates is usually chosen for structural applications where its use will lead to a lower overall cost of construction than that would be expected with the use of normal-weight concrete. LWCs are typically weaker than normal weight concretes; however, several researches have

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shown that the advantages of light-weight aggregates far outweigh the advantages of normal-weight aggregates such as high strength-to-density ratio, durability, fire resistance, and good thermal performance [18]. The low compressive strength of LWC is mostly due to the porous nature of the lightweight aggregate and the resulting high void ratio of the concrete mix. Therefore, more cement paste is required for LWC to produce desired workability and strength, and reduction in capillary absorption, chloride content, and sulfate expansion. The porous aggregate reduces the density of the lightweight aggregate concrete; however, it easily fractures under stress. Hence, understanding the behavior of LWC under various environmental conditions would enable engineers to use it in structural applications.

Many investigations have been conducted on the mechanical properties, thermal conductivity and sound insulation of light-weight cement concretes [3,19,20]. Sengul et al. [3] investigated the mechanical properties and thermal conductivity of LWC using expanded perlite. The results of the experimental program revealed that the compressive strength and elastic modulus (EM) decreased as the perlite content increased. Also, the thermal conductivity was improved with the use of perlite in mixes. Tian et al. [21] investigated the mechanical properties and dynamic modulus of high strength concrete with partial replacement of coarse aggregates instead of lightweight aggregate presaturated water and polymer emulsion (i.e. 15%, 30%, 45% and 70% by vol.). According to their study, as the percentage of replacement increased, EM, dynamic modulus of elasticity, and mechanical properties of high-strength concrete decreased. In the lower amount of replacement, the reduction in the properties were not significant; however, in the 45% and 70% level of replacement, the reduction in the properties were obvious. Shafigh et al. [22] studied the possibility of using by-products (i.e., fly ash and limestone powder) in lightweight aggregate concrete and determined the properties of the mixes. Tests results showed that using high-volume fly ash significantly reduced the short-term mechanical properties; however, using limestone powder improved the compressive strength in the majority of mixes. It is worth noting that the chemical characteristics of by-products can also affect the mechanical properties of concrete [23].

In the past few decades, researchers introduced a new type of concrete, polymer concrete (PC), which shows superior mechanical properties compared to those of cement concrete. PC exhibits a higher compressive, tensile, and flexural strength, fast curing, and it provides better protection in corrosive environments [24] and shows better vibration damping properties [25–27] as compared to conventional cement concrete. PC is also used in high-performance applications to repair and rehabilitate structures as an alternative to fiber reinforced polymers and steel reinforced piles [28]. Agavrilaoie et al. [29] investigated the mechanical behavior of new type of PC using epoxy polyurethane acryl matrix. They concluded that PC is a lightweight concrete while possessing high durability performance against chemical aggression and freeze–thaw cycles. These advantages make PC suitable for use as insulation and waterproofing material, and in industrial construction where thermal and chemical protective cover is needed.

Due to the higher cost of PC, researchers have been searching for a way to reduce the cost and enhance the properties of PC by adding different fillers. Ferdous et al. [30] evaluated the mechanical properties of PC by mixing three types of filler materials (fly ash, fire retardant filler, and hollow microsphere). The physical, mechanical properties and durability were evaluated with the change in the resin-to-filler ratio. The results revealed that by increasing the filler ratio, the applications became more cost-effective and the thermal and durability properties improved; however, this resulted in a reduction in mechanical properties. Ferdous et al. [31] also studied the effect of resin-to-filler ratio and

matrix-to-aggregate ratio on mechanical properties and durability of epoxy-based polymer concrete to determine the proper mix design. They reported that the resin-to-filler ratio has significant effect on the distribution of aggregates and a decrease in the matrix-to-aggregate ratio causes a reduction in mechanical and durability properties. Past researches have shown that temperature is a significant parameter that can affect the performance of engineering materials [32,33]. Khotbehsara et al. [32] investigated the effect of in-service elevated temperatures on the mechanical properties and microstructure of particulate-filled epoxy polymers, which contained a fire retardant and fly ash fillers. They concluded that the particulate-filled epoxy resin exhibits good performance in the retention of mechanical properties at elevated temperatures which is beneficial for civil engineering applications.

Although there are a few standards, such as ACI 211.2 [34], that provide methods for designing LWC mixes, currently there are no such reference documents to design LWPC, as the use of polymer concrete in construction is relatively new. To achieve serviceable, durable, and economic construction with LWPC, understanding the mechanical properties of LWPC is needed. The primary aim of this study was to investigate the quality, integrity, durability, and mechanical properties of LWPC and their variation by temperature to understand the short- and long-term behavior. To study all these parameters, over 170 specimens were prepared and tested.

2. Experimental program

2.1. Materials and specimen preparation

The maximum size and specific gravity of porous lightweight aggregates were 19 mm and 1.4, respectively. Natural river sand with specific gravity of 2.65 and the nominal maximum size of 4.75 mm, meeting the requirement of ASTM C33 [35], was used as the fine aggregate. Previous studies [36–38] reported that the coarse to fine aggregate ratio was in the range of 0.4–1.0 (by weight) in the mix design of LWC according to ACI 211.2 code [34]. Because there is currently no design code for lightweight polymer concrete, a reasonable assumption has made. In the current study, the specific gravity ratio of the porous lightweight aggregate to fine aggregate was approximately 0.5. As such, in the mix design the weight ratio of the porous lightweight aggregate to fine aggregate was selected as 0.5:1.

The epoxy resin was used as the adhesive material with a ratio of base/hardener mix 1:0.58 by weight [39]. The 7-day compressive and splitting-tensile strength of polymer specimens cured at room temperature was approximately 70 MPa and 35 MPa, respectively. Four different polymer contents -10%, 12%, 14%, and 16%-were used to study the influence of the binder content. For each polymer content, the specific amount of base and hardener were initially mixed together. Following this, the resin was blended with the aggregates to prepare the LWPC mix. The mix was filled in molds in three layers and each layer was pounded 25 times. After the specimens were demolded, they were cured at room temperature (25 ± 3 °C) for seven days. The mix designs and notations for the four types of LWPCs are presented in Table 1.

Cylindrical specimens with dimensions of 76×152 mm, 76×76 mm, and 152×40 mm were made for the compression, splitting-tensile, and impact tests, according to ASTM C39 [40], ASTM C496 [41], and ACI 544 [42], respectively. For flexural test, the prismatic specimens with the size of $75 \times 75 \times 500$ mm were cast according to ASTM C78 [43]. For ultrasonic and electrical conductivity tests, the cubic specimens with the dimension of 100 mm were prepared.

Table 1

Notation and mix design of various types of LWPC tested at different temperatures.

Notation	Lightweight coarse aggregate (by weight) (%)	Fine aggregate (by weight) (%)	Polymer ratio (%)	Temperature (°C)
LWPC10/−15	30.0	60.0	10	−15
LWPC10/+5	30.0	60.0	10	+5
LWPC10/+25	30.0	60.0	10	+25
LWPC12/−15	29.3	58.7	12	−15
LWPC12/+5	29.3	58.7	12	+5
LWPC12/+25	29.3	58.7	12	+25
LWPC14/−15	28.7	57.3	14	−15
LWPC14/+5	28.7	57.3	14	+5
LWPC14/+25	28.7	57.3	14	+25
LWPC16/−15	28.0	56.0	16	−15
LWPC16/+5	28.0	56.0	16	+5
LWPC16/+25	28.0	56.0	16	+25

2.2. Test setup

The compressive strength of specimens was determined using a 3000-kN uniaxial testing machine (UTM) in accordance with ASTM C39 [40]. The axial strains were measured by a linear variable differential transducer (LVDT) during the test. According to ASTM C496 [41], splitting-tensile strength tests were conducted on cylindrical specimens. The prismatic specimens were tested to determine the flexural strength under three-point bending according to ASTM C78 [43]. The impact energy of specimens was determined with the use of drop weight impact test which is suggested by ACI Committee 544 [42]. A 20.4 N.m energy was absorbed by the specimen in each drop and this cycle was repeated until the complete failure occurred. The total number of drops indicated the impact energy of the specimen.

An ultrasonic pulse velocity (UPV) apparatus was used to generate the longitudinal elastic wave pulses to measure the transit time through the specimens according to ASTM C597 [44]. To evaluate the durability of steel bars inside concrete against the attack of chloride ion and corrosion, an electrical resistivity apparatus was used to perform AC-Impedance spectroscopy as illustrated in Fig. 1. This instrument applies an alternating current at an intended frequency without causing any disruption and measures the voltage between the two sides of the concrete specimen and the impedance (Z) can be calculated [45]. The resistivity of LWPC specimens was measured with the frequency of 10 kHz.

3. Results and discussions

3.1. Hardened density

According to ASTM C125 [46], density is explained as the mass of a material divided by the volume of a skeleton plus permeable and impermeable pores. The density of LWPC specimens was mea-

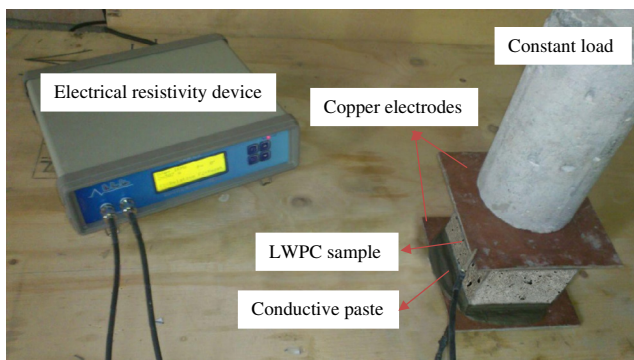
sured and compared with that of polymer concrete (PC) specimens formerly investigated [47], which are presented in Table 2. It is worth noting that there is no available data from previous studies on the density of PC mix with 16% polymer content. The results of this comparison show that, for a given polymer content, the density of LWPC was almost 20% lower than that of PC. This weight reduction is quite significant and can be beneficial in reducing both the damage sustained by structures under certain types of loading (e.g. earthquake) and overall cost of construction.

3.2. Failure modes

Fig. 2 shows the specimens tested at +25 °C after peak stress to illustrate the trends of crack propagation and lateral expansion. The image shown in Fig. 2(a) was taken at the peak stress and it illustrates that the initial crack occurred at the top of the specimen. As the displacement increased, this crack propagated (Fig. 2(b)) and with further increase in displacement (Fig. 2(c)) additional cracks were formed at various parts of the specimen and the middle-height region started to show signs of bulging. As the test continued, the cracks connected to each other and this resulted in the failure of the specimen (Fig. 2(d)). It was observed that for specimens tested at lower temperatures (+5 °C, and −15 °C), more brittle failure and a sudden interface debonding between aggregates and polymer occurred and as such, no lateral deformation was visually observed. However, specimens tested at +25 °C showed visible lateral deformations and exhibited a prolonged softening behavior in their stress–strain curves.

3.3. Compressive behavior

The compression test results of LWPC with 10%, 12%, 14%, and 16% polymer contents tested at various temperatures (−15 °C, +5 °C, and +25 °C) are shown in Fig. 3. To find out the failure point of the stress–strain curves of the specimens, after the cracks completely propagated, the compressive strength drastically decreased and the failure point is defined as the point just before this sudden reduction occurred in the curves. The compressive strength increased with decreasing the temperature. Decreasing the temperature from +25 °C to +5 °C and +5 °C to −15 °C resulted in an

**Fig. 1.** Electrical conductivity setup.**Table 2**

Density of PC and LWPC.

Epoxy resin by weight (%)	Density (kg/m ³)		Decrement density ratio (%)
	LWPC	PC	
10	1735	2135	18.7
12	1756	2184	19.6
14	1780	2211	19.5
16	1815	–	–

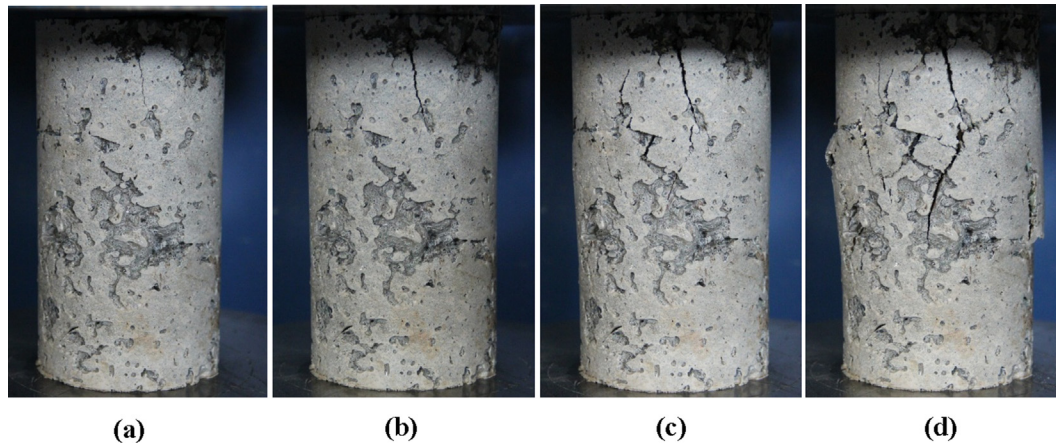


Fig. 2. The crack propagation process of LWPC16/+25 after peak axial stress (a) initial crack (b) opening modes, (c) sliding mode (d) failure mode.

increase in the compressive strength by approximately 4% and 9%, respectively, in all series. The significant reason for high compressive strength at lower temperatures was the increase in the interface bond strength between the aggregates and the polymer. Viklund et al. [48] showed that increasing temperature can cause a reduction in the size and volume of pores due to increased epoxy resin mobility at higher temperatures, and this leads to a decrease in the compressive strength. As shown in Fig. 3, increasing the polymer content caused an increase in the compressive strength and corresponding axial strain. The rate of increase in the compressive strength and corresponding strain decreased with increasing polymer content, and there was only a slight difference between the compressive strength and strain of specimens with 14% and

16% polymer contents. The compressive strength, axial strain corresponding to maximum strength, and failure strain of all specimens are provided in Table 3.

A comparison was made between the compressive strength results of LWPC and those of the polymer concrete with larger coarse aggregate (PCL) manufactured with the same size aggregates and polymer content, and tested at the same temperature [39]. The comparison shows that the compressive strength of LWPC was 10% to 20% lower than that of the corresponding PCL depending on the test temperature and polymer content. The comparison also showed that the temperature played more influential role on the compression test of PCL than that of LWPC.

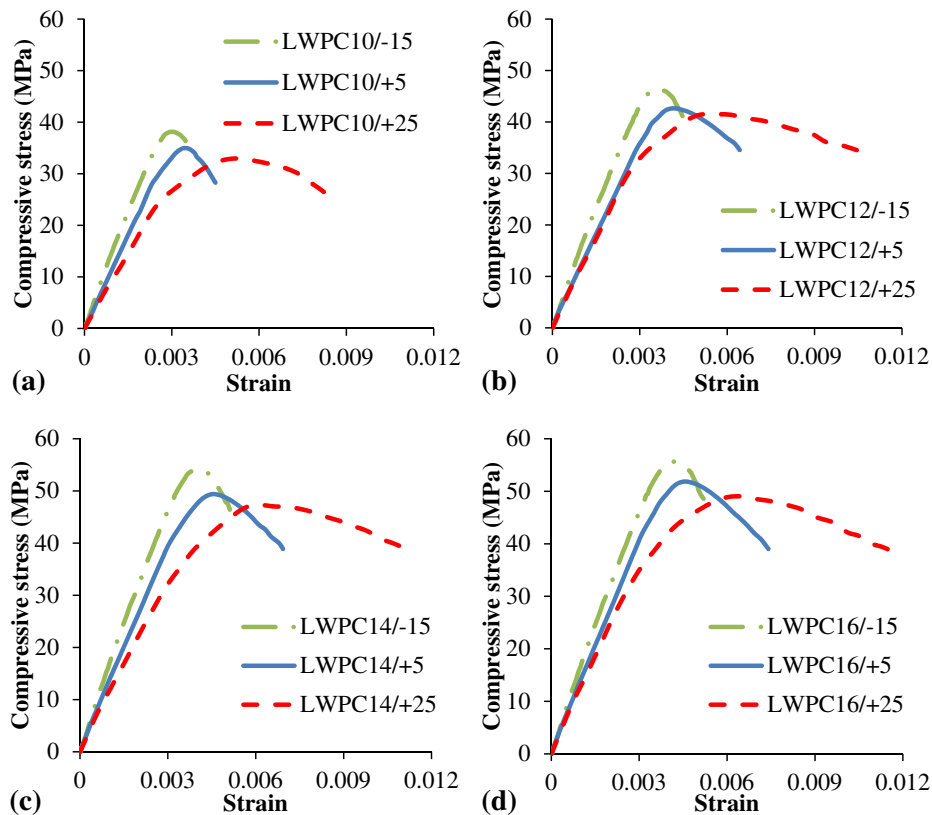


Fig. 3. Compressive stress–strain curve for LWPC having (a) 10%, (b) 12%, (c) 14%, and (d) 16% epoxy resin.

Table 3

Properties of different LWPC mixes tested at different temperatures.

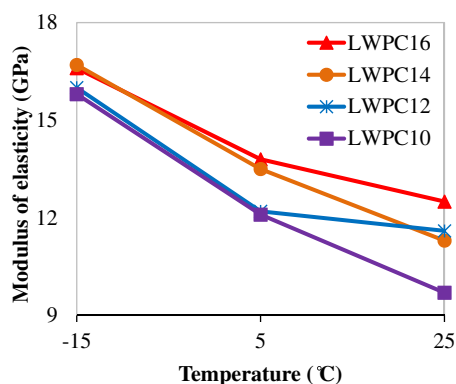
Specimen	Maximum compressive stress (MPa)	Strain at maximum stress (10^{-3})	Failure strain (10^{-3})
LWPC10/−15	38.2	3.03	3.72
LWPC10/+5	34.9	3.39	4.50
LWPC10/+25	33.0	5.23	8.57
LWPC12/−15	46.4	3.65	4.60
LWPC12/+5	42.6	4.15	6.43
LWPC12/+25	41.5	5.56	10.52
LWPC14/−15	54.1	4.06	5.11
LWPC14/+5	49.3	4.48	6.93
LWPC14/+25	47.3	6.13	11.17
LWPC16/−15	55.7	4.21	5.35
LWPC16/+5	51.8	4.52	7.41
LWPC16/+25	49.0	6.49	11.72

3.4. Elastic modulus (EM)

The EM of LWPC specimens was calculated based on the initial slope of the stress–strain curves (approximately 30%–40% of the maximum compressive strength) [39,49]. As shown in Fig. 4, the EM increased with decreasing temperature from +25 °C to −15 °C. There was only a slight difference (i.e. approximately 6%) between the EM of various types of LWPC specimens tested at the temperature of −15 °C. On the other hand, this difference for specimens tested at +5 °C and +25 °C was 14% and 29%, respectively. These observations demonstrate that with a decrease in the tested temperature, the difference between the EM of different types of LWPC becomes negligible. This does not agree with the authors' previous study on polymer concrete [39], where it was found that the difference between EM of PCL and polymer concrete with smaller coarse aggregate (PCS) at higher temperatures (+25 °C and +65 °C) was negligible. This is attributed to several reasons including significant differences in the aggregate size and distribution, volume fraction, surface characteristics, air content, and bond strength with matrix in PC versus LWPC, as well as the differences in the test temperature. Polymer concrete is more rigid at lower temperatures; however, at temperatures higher than +25 °C, it shows a softer behavior and it completely loses its internal resistance at 65 °C [39]. Additional studies are recommended to better understand the influence of temperature on EM.

3.5. Energy absorption

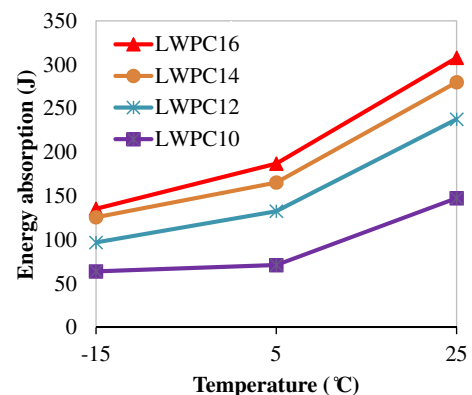
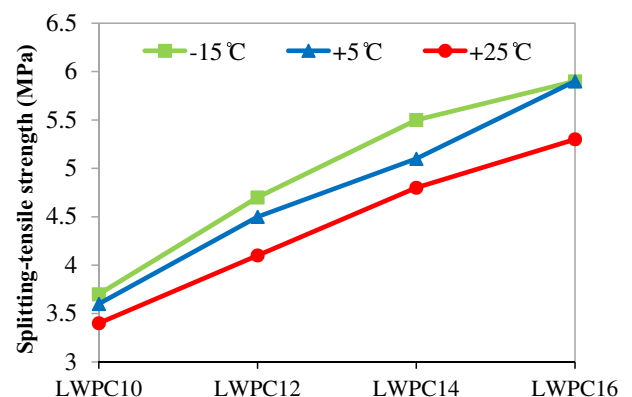
Energy absorption is the amount of absorbed energy per unit volume by the specimen defined as the area under stress–strain

**Fig. 4.** Modulus of elasticity of LWPC having different polymer content versus temperature.

curve up to failure strain [50–52]. It is shown in Fig. 3 that the ductility of concrete decreased and the softening behavior became more abrupt with decreasing temperature. For specimens tested at +5 °C to −15 °C, after the peak stress, the specimens lost their strengths rapidly. The energy absorption of all specimens is shown in Fig. 5. At a given temperature, increasing in the polymer content led to increasing the energy absorption of LWPC, as both stress and strain increased. Decreasing the temperature from +25 °C to +5 °C, the energy absorption decreased significantly (i.e. in the range of 40% to 52% depending on polymer content). In the authors' previous study on normal weight PC [39], the maximum energy absorption was obtained at a temperature of +25 °C, which is in agreement with the current study. As can be seen in Fig. 5, a decrease in the temperature from +5 °C to −15 °C resulted in a smaller decrease, in the range of 10% to 28%, in the energy absorption.

3.6. Splitting-tensile strength

The results of splitting-tensile strength for LWPC mixtures are depicted in Fig. 6. An increase in the polymer content and a decrease in temperature led to increasing in the splitting-tensile strength. There was only a slight difference (i.e. 3–8%) between the splitting-tensile strength of specimens tested at −15 °C and +5 °C, as in both temperatures, the specimens were frozen and this led to an increased interface bond. At +25 °C, with each 2% increase in the polymer content from 10% to 16%, the splitting-tensile strength increased by 21%, 17%, and 10%, respectively. At all temperatures, the effect of the change in the polymer content was more significant as it changes from 10% to 12% than that from 14% to 16%.

**Fig. 5.** Energy absorption of different types of LWPC.**Fig. 6.** Splitting-tensile strength of LWPC.

Several researchers suggested a relationship between the different powers of compressive and splitting-tensile strengths. Gholampour and Ozbakkaloglu [53] provided a summary of the mechanical properties of conventional concrete considering design codes for the prediction of splitting-tensile based on their compressive strength. In ACI 318 [54], for cement concrete $f_{st} = 0.56 \sqrt{f_{cm}}$ and for high-strength cement concrete the equation is $f_{st} = 0.6-0.7 \sqrt{f_{cm}}$ [55,56] where f_{st} is the mean splitting-tensile strength (MPa) and f_{cm} is the mean compressive strength (MPa). According to Jafari et al. [39], for polymer concrete, the recommended equation is $f_{st} = 0.8 \sqrt{f_{cm}}$. However, some other researchers suggested that the relationship between compressive strength and splitting-tensile strength with the power of (2/3) has higher accuracy than that with the power of (1/2) [57,58]. Neville [57] reported that for conventional cement concrete, the splitting-tensile strength is equal to $f_{st} = 0.23 (f_{cm})^{2/3}$. In this study, the relationship of splitting-tensile strength and compressive strength for LWPC was obtained with the power of (2/3) as shown in Fig. 7, as this led to a higher accuracy than that attained with the power of (1/2). The constant value for LWPC was found to be 0.37, which indicates that LWPC exhibits a higher splitting-tensile strength compared cement concrete.

3.7. Flexural strength

Fig. 8 shows the flexural strength of different types of LWPC. The results illustrate that by increasing the polymer content from 10% to 16% at -15°C , $+5^\circ\text{C}$, and $+25^\circ\text{C}$, the maximum flexural strength increased 63%, 66%, and 53%, respectively. In general, a decrease in temperature at any polymer content caused an increase in the flexural strength. This increase was more significant when the temperature dropped from $+25^\circ\text{C}$ to $+5^\circ\text{C}$ as from $+5^\circ\text{C}$ to -15°C . In this study, the relationship of flexural strength and compressive strength for LWPC was obtained with the power of (2/3) as shown in Fig. 9, as this led to a higher accuracy than that attained with the power of (1/2). The flexural strength of LWPC, expressed as a function of compressive strength, was $f_r = 0.40 (f_{cm})^{2/3}$ which is slightly lower than the suggested value for cement concrete by Ahmad and Shah [59] as $f_r = 0.44 (f_{cm})^{2/3}$ where f_r is the mean flexural strength (MPa). According to literature [57,59], for conventional concrete, the ratio of flexural strength to splitting-tensile strength is 1.9; however, for LWPC, this value is around 1.0. The reason is partially because of the size of flexural specimens that prepared for this study and partially because during casting LWPC samples, the segregation occurred as the polymer move toward the top of the specimen due to the lower density of polymer compared to the aggregates. For flexural specimens, this phenomenon is more obvious as the bottom of the specimen become weak and the cracks propagated rapidly in the interfacial zone due to the lack of binder.

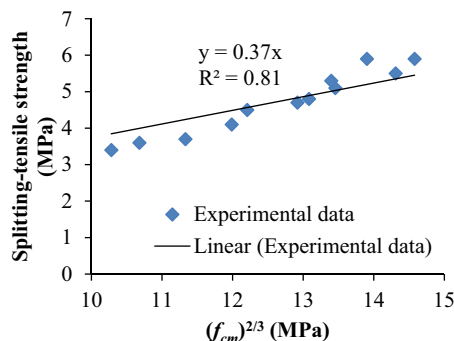


Fig. 7. Relationship between compressive strength and splitting-tensile strength.

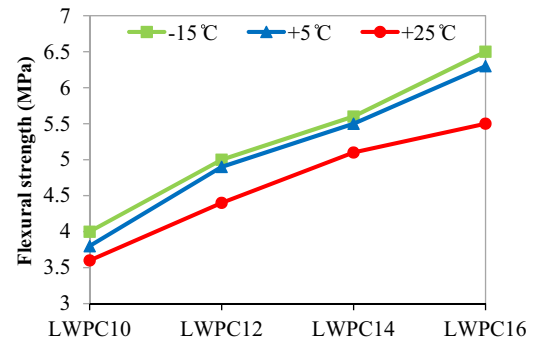


Fig. 8. Flexural strength of LWPC.

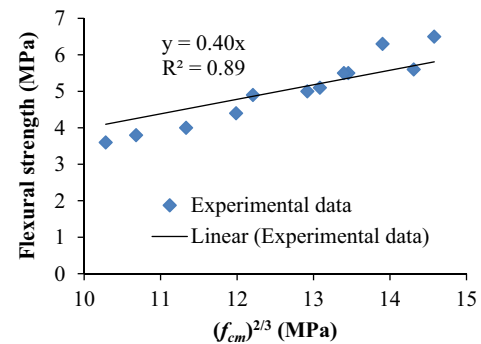


Fig. 9. Relationship between compressive strength and flexural strength.

3.8. Impact energy

The impact energy of LWPC specimens is presented in Fig. 10. As illustrated in this figure that the impact energy of specimens increased with an increase in the polymer content. The difference between the impact energy of LWPC12 and LWPC10 was much higher than that between LWPC14 and LWPC12, which was in turn higher than the difference between LWPC16 and LWPC14. For example, at $+25^\circ\text{C}$ temperature, increasing the polymer content from 10% to 12% and 12% to 14% led to an increase in the impact energy by 32% and 14%, respectively. However, at the same temperature, an additional increase in the polymer content from 14% to 16%, led to only 9% increase in the impact energy. When polymer was added in larger amounts, the bond between the polymer and aggregates increased and the adhesive material was able to com-

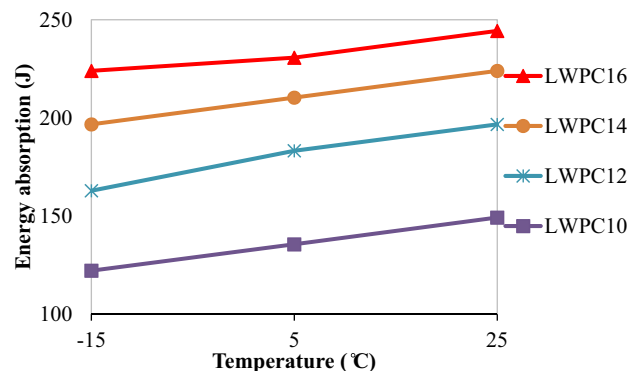


Fig. 10. Impact energy of LWPC mixes at different temperatures.

pletely coat the aggregates. As a result, more energy was required to break this bond and cause cracks in the specimens. Experimental observations showed that after initial cracks occurred on the surface of specimens, they rapidly propagated and connected to each other in the next two or three cycles leading to the complete failure of the specimen. Lower impact energy of LWPC with lower polymer content can also be attributed to the presence of large number of voids and their connection inside the specimen. Moreover, increasing the temperature from $-15\text{ }^{\circ}\text{C}$ to $+25\text{ }^{\circ}\text{C}$ caused an increase in the impact energy. This is because, at low temperatures the viscoelastic property of polymer content decreased and hence less energy was required for the initiation and development of cracks, which led to a lower impact energy.

3.9. Ultrasonic pulse velocity

Generally, UPV decreases as the voids inside the specimens increase. The ultrasonic pulse velocities of LWPC of this study were determined to be in the range of 3162–3432 m/s. As can be seen in Fig. 11, UPV increased with increasing polymer content, as the voids were filled with polymer and the adhesive material firmly bonded the aggregates together. The comparison between UPV of LWPC samples showed that the low UPV value is partially due to the internal air voids in concrete and partially due to the voids inside porous aggregates. Several researchers have proven that there is a relationship (linear or exponential) between the compressive strength and UPV [60,61]. Fig. 11 depicts the linear relationship between the compressive strength and UPV for LWPC obtained in the current study:

$$f_{cm} = 58V - 149 \quad (1)$$

where f_{cm} is the mean compressive strength (MPa), and V is the UPV (km/s). For conventional concrete, the UPV value above 4.0 km/s shows excellent and homogenous concrete [60–63].

3.10. Electrical resistivity

The electrical resistivity test was used to measure the ion passed through the LWPC and evaluate the probability of corrosion inside the concrete. The electrical resistance of LWPC specimens is presented in Fig. 12. The results show that the electrical resistance of LWPC specimens increased with increasing the percentage of polymer content, which led to lower porosity. Each 2% increase in the polymer content from LWPC10 to LWPC16 increased the electrical resistance 16%, 7% and 6%, respectively. It is worth noting that the electrical resistivity of all LWPC mixes were higher than $120\text{ }\Omega\text{ m}$, indicating that the corrosion of steel bars inside concrete would not be probable [64].

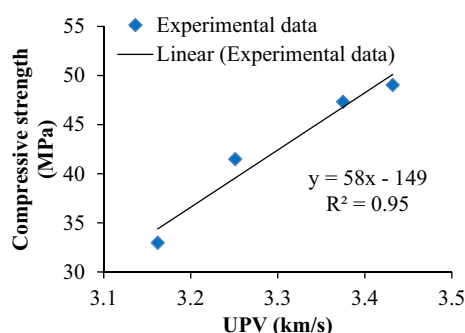


Fig. 11. Relationship between compressive strength and UPV for LWPC.

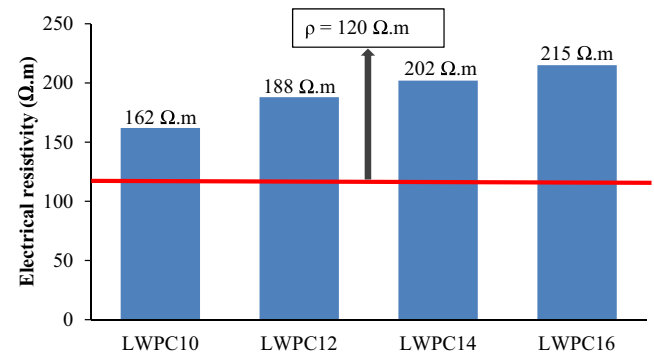


Fig. 12. Results of electrical resistivity of LWPC test at $+25\text{ }^{\circ}\text{C}$.

4. Probabilistic models for destructive tests of LWPC

4.1. Variables for prediction

Here, the dependency of the mechanical properties obtained through destructive tests to the temperature, polymer content, and compressive strength of LWPC was investigated. Temperature, polymer content, and compressive strength and their effects on LWPC indicated the influential variables used in this investigation. All possible experimental and material properties were considered in this research; nevertheless, some of them were eliminated because of their statistical insignificance. In Figs. 14–16, vertical axis represents the splitting-tensile strength (f_t), flexural strength (f_r) and impact energy (IE). The horizontal axis depicts the experimental properties such as polymer content (P), temperature (T) and compressive strength (f_{cm}). Correlation factor (R^2) of the trend lines shows the effect of each parameter that should be participated in the empirical equations. It should be noted that these figures provide only an insight into the trends between parameters and variables utilized for modelling in RT software so, they should not be utilized to establish relationships between the model parameters and variables. Therefore, the dependency of the parameters is discussed in detail in the following sections.

4.2. Dependence of destructive test parameters on polymer content, temperature, and compressive strength

An increase in the polymer content is associated with a clear increase in mechanical properties. This is confirmed by Fig. 13, which represents that the polymer content and a linear regression line for the mechanical properties of LWPC. Moreover, increasing the temperature leads to decrease the splitting-tensile and flexural strength values and increase the impact energy as shown in Fig. 14. In addition, increasing the compressive strength, the most effective factor compared to other destructive tests, led to an increase in splitting-tensile strength, flexural strength, and impact energy as shown in Fig. 15(a)–(c) respectively. All of the figures revealed the great dependence of destructive test parameters on polymer content, temperature, and compressive strength.

4.3. Predictive models

To attain the best estimation of destructive test properties of LWPC, empirical equations are presented below. These equations reported by way of regression using Eq. (2). A stepwise regression method was performed to specify the most statistically significant variables. In Eq. (2), X_1 to X_n are predictor variables based on the mix design, environmental situation and compressive strength of the LWPC, and a_1 to a_n are regression coefficients. Eq. (3) is the nat-

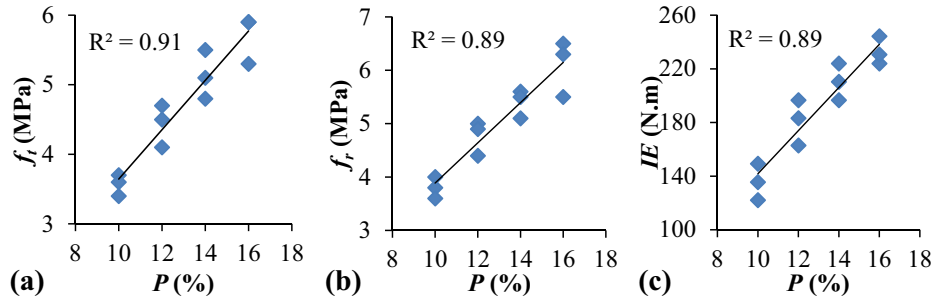


Fig. 13. Dependency of (a) splitting-tensile strength, (b) flexural strength, (c) impact energy to the polymer content.

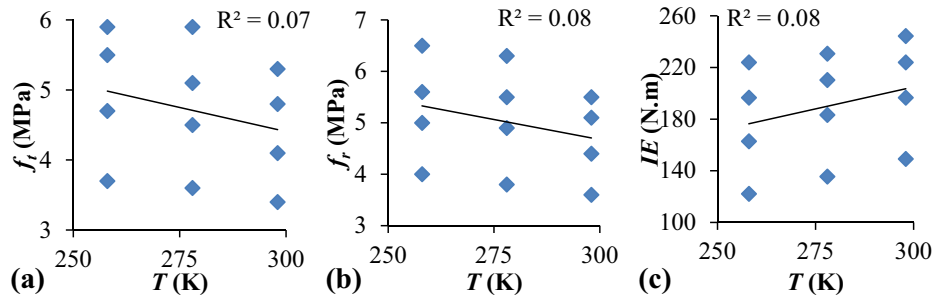


Fig. 14. Dependency of (a) splitting-tensile strength, (b) flexural strength, (c) impact energy to the temperature.

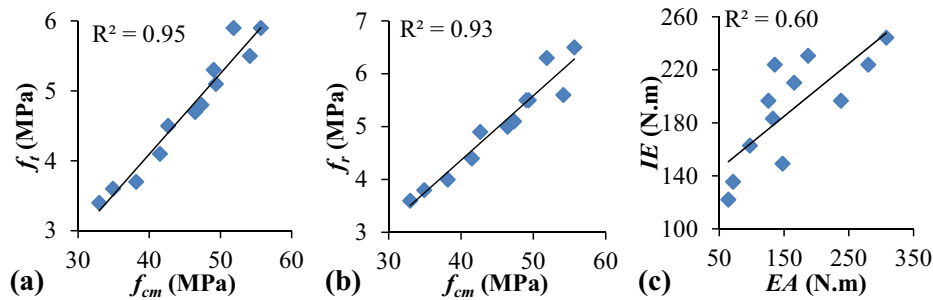


Fig. 15. Dependency of destructive tests to (a) and (b) compressive strength and (c) energy absorption.

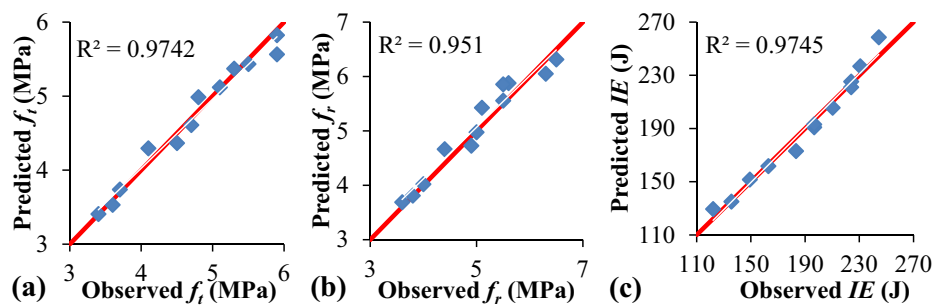


Fig. 16. Comparison between the measured and predicted values (a) splitting tensile strength, (b) flexural strength, and (c) impact energy.

ural logarithmic form of Eq. (2) to model a linear relation among the parameters which previously mentioned.

$$f(X_1, \dots, X_n) = a_1(X_1)^{a_2}(X_2)^{a_3} \dots (X_n)^{a_{n+1}} \quad (2)$$

$$\ln(f(X_1, \dots, X_n)) = c + a_2 \ln(X_1) + a_3 \ln(X_2) + \dots + a_{n+1} \ln(X_n) \quad (3)$$

Furthermore, the highest value of coefficient of variation was removed from the model. The quality of the model was then controlled by way of the prediction versus experimental graphs. In

addition, the mean of standard deviation of the model error should not have a great change and coefficient of variation of regression should be in an allowable range; if not, the prior model is more valuable [65–67].

The regression coefficients were set to their respective mean estimation in the suggested predictive equations. This regression was predicted according to the effect of various parameters on the splitting-tensile strength, flexural strength and impact energy of the LWPC presented in Eqs. (4)–(6), respectively. The stepwise

omission procedure was used to attain an agreement between model simplicity and model accuracy [68,69].

$$f_t = 1.05 \times \left(0.14 \ln(P) - \frac{2.7}{T} \right) \times (f_{cm})^{2/3} \quad (4)$$

$$f_r = 1.15 \times \left(0.14 \ln(P) - \frac{6.5}{T} \right) \times (f_{cm})^{2/3} \quad (5)$$

$$IE = (P)^{0.94} \times (T)^{0.39} \times (EA)^{0.12} \quad (6)$$

where f_t is the splitting-tensile strength (MPa), f_r is the flexural strength (MPa), f_{cm} is the mean compressive strength (MPa) obtained from the experiments, P is the ratio of polymer content (i.e., 14), T is the temperature (K). The comparison between the measured and predicted values by Eqs. (4)–(6) are shown in Fig. 16. The values of R factor, coefficient of variation (COV) of standard deviation (sd), and mean (μ) of standard deviation for models are presented in Table 4. As can be seen, a high correlation between the measured and predicted values was obtained in all tests.

Table 4
Statistics of predictive equations.

Predictive model	R-factor	COV(sd)	μ (sd)
Splitting-tensile strength	0.96	0.289	0.011
Flexural strength	0.94	0.289	0.015
Impact energy	0.99	0.316	0.038

Table 5
Results of ANOVA for the compressive strength LWPC.

Control factor	Degrees of freedom	Sum of square	Variance	Variance ratio (F-value)	Contribution (%)
Polymer content, P (%)	3	523	174.0	580	87.7
Temperature, T (°C)	2	72	35.9	119	12.0
Error	6	2	0.3	–	0.3
Total	11	596	–	–	100

Table 6
Results of ANOVA for the splitting-tensile strength LWPC.

Control factor	Degrees of freedom	Sum of square	Variance	Variance ratio (F-value)	Contribution (%)
Polymer content, P (%)	3	7.88	2.63	210	91.7
Temperature, T (°C)	2	0.63	0.32	25	7.4
Error	6	0.07	0.01	–	0.9
Total	11	8.59	–	–	100

Table 7
Results of ANOVA for the flexural strength LWPC.

Control factor	Degrees of freedom	Sum of square	Variance	Variance ratio (F-value)	Contribution (%)
Polymer content, P (%)	3	8.59	2.86	127	89.7
Temperature, T (°C)	2	0.85	0.43	19	8.9
Error	6	0.13	0.02	–	1.4
Total	11	9.58	–	–	100

Table 8
Results of ANOVA for the impact energy LWPC.

Control factor	Degrees of freedom	Sum of square	Variance	Variance ratio (F-value)	Contribution (%)
Polymer content, P (%)	3	15,885	5295	519	91.2
Temperature, T (°C)	2	1472	736	72	8.4
Error	6	61	10	–	0.4
Total	11	17,418	–	–	100

4.4. ANOVA analysis

The ANOVA was used to determine the optimum conditions of the main test parameters in different experimental tests [39,70]. The ANOVA results for the compressive, splitting-tensile, flexural, and impact strengths for different polymer ratios of LWPC mixes tested at various temperatures are shown in Tables 5–8, respectively. Based on the results, in LWPC, the polymer ratio played a significant role on the mechanical properties, with the contributions of 88%, 92%, 90%, and 91% for the compressive, splitting-tensile, flexural strengths, and impact energy, respectively. However, Jafari et al. [39] reported that in PC, temperature had a major influence on the compressive, splitting-tensile, and flexural strengths with percent contributions of 70%, 85%, and 85%, respectively. ANOVA was also used to statistically evaluate significant parameters. The frequency value (F-value) for each parameter was used in statistics, which forms the quality characteristics. The observations indicate that the F-values of two mix design parameters were all higher than $F_{0.05,(2,5)} = 5.79$ which shows that they had a statistical effect on the mechanical behaviors of LWPC.

5. Summary and conclusions

This research has studied the experimental and analytical methods to determine the mechanical properties of different LWPC mix designs. In addition, the optimization method has been used for evaluation of the LWPC mixtures. The following conclusions are drawn:

- The density of LWPC is approximately 20% lower than that of PC. This can help reduce the overall cost of construction and the damage sustained by structures under certain types of loading (e.g. earthquake).
- Increasing the polymer content from 10% to 16% leads to an increase in the mechanical properties, ductility, and energy absorption of LWPC specimens, with observed increases of 32% in compressive strength, 57% in splitting tensile strength, 52% in flexural strength, and 69% in energy absorption. The rate of increase in the compressive strength decreases with increasing polymer content, and only a slight difference was observed between the compressive strengths of mixes with 14% and 16% polymer contents. The non-destructive tests reveal that the porosity of specimens reduces as the polymer content increases.
- The reduction of the testing temperature from +25 °C to −15 °C causes an increase in the mechanical properties of specimens, with observed increases of 12% in compressive strength, 14% in splitting tensile strength, 14% in flexural strength. However, a significant decrease in the impact resistance, energy absorption, and ductility is observed with decreasing temperature.
- The difference between the splitting-tensile and flexural strengths of LWPC is very low and the ratio is higher than 0.9; however, for conventional concrete, this ratio is typically around 0.5–0.6.
- The results of ANOVA revealed that the polymer ratio had more substantial influence on the results of destructive test in comparison with temperature particularly in the flexural strength and splitting-tensile tests. The equations suggested in this research provide accurate estimations of the mechanical properties (i.e., splitting-tensile and flexural strength), and impact energy of LWPC based on experimental parameters and compressive strength tests result, which make them applicable in order to use in the pre-design of LWPCs.

This paper has provided beneficial information on the mechanical properties of LWPC and their variation by temperature. Although the results are quite positive, they also point to the importance of careful design and implementation of LWPC, as the mechanical properties of the material can degrade significantly under certain conditions.

6. Future work

For future research, the reaction mechanism of polymerization (from the time that epoxy and resin are mixed until the test day) will be studied using the proposed instrument by Akhoundi et al. [71]. In this approach, the proposed materials are tagged with Cy3 and Cy5 fluorescent label dyes. The fluorescent images are taken by the confocal microscope setup to provide valuable information on polymerization reaction. Moreover, the effect of adding micro-fillers are analyzed with this method to reduce the overall cost of polymer applications.

CRedit authorship contribution statement

Fatemeh Heidarneshad: Conceptualization, Investigation, Validation, Writing - original draft, Visualization. **Khashayar Jafari:** Conceptualization, Investigation, Validation, Writing - original draft, Visualization. **Togay Ozbakkaloglu:** Conceptualization, Supervision, Writing - review & editing.

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