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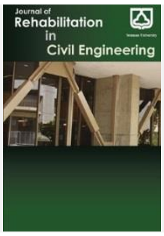

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Mechanical Properties of Self-Compacting Lightweight Concrete Containing Pumice and Metakaolin

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ABSTRACT

Self-compacting lightweight concrete (SCLC) is a novel type of concrete that combines the benefits of the lightweight and self-compacting concrete (SCC) types. In this research, the optimal amount of metakaolin used in lightweight concrete containing pumice has been obtained based on the best concrete performance in terms of the greatest simultaneous increase in compressive, tensile and flexural strengths. After choosing the SCLC mixing scheme, L-Box, V-Funnel, Slump flow, and T_{50} tests were performed to investigate the flowability, passing ability, viscosity, and concrete resistance against segregation. Then, the mechanical properties of SCLC have tested by replacing metakaolin with 0, 5, 10, 15, and 20% by weight of cement. The research results have demonstrated that metakaolin enhances the mechanical strength of SCLC. In addition, by adding metakaolin in the amount of 15% cement weight, the process of improving concrete strength continues. The 28-day SCLC specimens containing 15% metakaolin had compressive, splitting tensile and flexural strength of 26%, 14%, and 11% higher than those of SCLC without metakaolin, respectively. Furthermore, formulas that can predict compressive strength, tensile strength, and flexural strength of 28-day SCLC containing metakaolin have been presented.

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1. Introduction

Concrete is one of the most extensively utilized construction materials, and effective measures are always taken to make the most significant use of this product by providing new technology and new processes. Self-compacting lightweight concrete (SCLC) has been employed for lightweight structures and earthquake resistance in recent decades. Further, the use of pozzolanic materials in concrete production has increased. In addition to lowering cement and energy consumption and greenhouse gas emissions, using pozzolan as an alternative to cement in concrete enhances the mechanical qualities of concrete, such as compressive strength at older ages and durability. Fly ash, silica fume, kiln slag, rice husk ash, metakaolin, and other additions are among them [1,2]. Bai et al. emphasized the careful selection of the composition and found that by doing this, the amount of cement decreases, but the compressive strength of concrete does not decrease [3]. Kim et al. used metakaolin to examine the durability and characteristics of high-strength concrete. They discovered that roughly 15% of the metakaolin had the most significant gain in resistance. They also demonstrated that metakaolin, rather than silica fume, can be employed cheaper [4]. Ramezanianpour et al. showed that concrete containing metakaolin has more resistance than concrete without metakaolin. Also, metakaolin increases the durability of concrete and reduces chloride emissions [5]. Many researchers investigated the role of metakaolin as a percentage replacement of cement. They used laboratory and software methods to evaluate the strength of concrete containing metakaolin and pozzolanic materials [6–14]. Shakiba et al. have investigated the effect of active pozzolan on the hydration and microstructure of natural pozzolan paste with high volume [15]. Askari et al. showed that the addition of lightweight aggregate reduces strength and increases water absorption in all cases [16]. Ghafor et al. demonstrated that the compressive, flexural, and tensile strengths of silica fume modified cement mortar had a favorable connection. [17]. Pundienė et al. discovered that adding 2.5-7.5% micro silica (MS) to a concrete mix containing cenospheres (CS) boosts the specimen's strength and shrinkage from 1.45-2.6 times and 0.14-0.41%, respectively. After curing at 1200°C, the specimen density drops from 1210 to 1140 kg/m^3 [18]. Nejati et al. used lica and sand to produce lightweight concrete. To increase the compressive strength of concrete made of light aggregates, they used silica fume, steel, and carbon fibers with a volume ratio of 0.5, 1, and 1.5% in the concrete mixture. They found that for a minimum compressive strength of 20 MPa, 10 percent by weight of cement should be allocated to the admixtures. Plus, they demonstrated the inclusion of steel and carbon fibers in the concrete mix to minimize slippage [19]. Al-Farttoosi et al. used pumice as a lightweight aggregate and silica fume as an additive in concrete construction. They found that using silica fume increased f_{cu}, f_{ct}, and f_r while marginally reducing equilibrium density. The findings revealed that lowering the quantity of pumice raises the equilibrium density and reduces $\mathrm{f_{cu}}$, $\mathrm{f_{ct}}$, and $\mathrm{f_r}$. This is due to the low weight of pumice compared to other mixed materials. In addition, increasing w/b lowers concrete's equilibrium density, f_{cu}, f_{ct}, and f_r [20]. In their study, Maleki et al. inquired about the mechanical behavior of fine aggregate and cement in the metakaolin grout. They found that increasing the confining pressure would further increase the metakaolin in the grout. Plus, they concluded that adding metakaolin to the sand grouted reduces the cohesion of sand while causing slight differences in the inner attrition angle of fine aggregate [21]. Kharun et al. showed that using light aggregates of scoria and lica increases the compressive strength of lightweight concrete to about 800 and 373 kg/m^2, respectively. [22]. Risdanareni et al. used metakaolin artificial lightweight aggregates (ALWA) to produce structural lightweight concrete. The results of their tests showed that the compressive strength of concrete decreases with the increase of ALWA content in the mixture [23]. Albidah et al. studied the performance of geopolymer concrete containing metakaolin at high temperatures. They showed that the residual compressive strength of the samples decreases with increasing temperature, and the rate of degradation of compressive strength with increasing exposure temperature is much lower than the modulus of elasticity [24]. Demirel et al. used pumice sand and metakaolin to produce structural lightweight concrete (SLWC). They showed that by adding 18% of metakaolin to cement ratio, the compressive strength increased. They used ratios of 5, 11, 18, and 25 percent. Finally, they obtained the effects of temperature and metakaolin on compressive strength [25]. Fowzi et al. used crushed light porcelain coarse aggregates to produce light concrete. They obtained the amount of 15% metakaolin to increase the mechanical strength of concrete [26]. In current years, the utilization of pozzolanic cement (a combination of Portland cement and a suitable pozzolan) to save energy and improve the durability and reliability of concrete has engrossed the heed of researchers. In addition, the researcher evaluated the strength of concrete using different methods [27–29].

Self-compacting concrete (SCC) is a flow and homogenous material with the benefits of high efficiency, high pumping capacity, shorter construction time, resistance to separation, assuring structural compaction, and increased structural member durability against causalities. The crucial properties of SCC could be mentioned environmental, thermal, and acoustic insulation, fire resistance, corrosion, frost resistance, fabrication of lightweight prefabricated components with complicated geometries, enhancement of final product quality, and economic savings in construction [30,31].

The primary design concepts of SCC mixtures are fluidity and stability. When light aggregates are used in this concrete form, there may not be enough inner energy to move it. Therefore, inside sections with high reinforcement density, concrete with light aggregates moves slightly slower than concrete with natural aggregates. However, SCLC designs meet the basic requirements of homogeneity and compaction uniformity in all cross-sectional areas [29]. Cement, coarse aggregate, fine aggregate, mineral additives, super-reducing water, viscosity modifiers, and fillers are all required to construct SCLC [27]. It should also have qualities such as a Slump flow of more than 600 mm without segregating, keeping fluidity at least 90 minutes, and the ability to withstand a 3% slope in the free horizontal plane. In addition, have qualities ability to be pumped in pipes, at least 100 meters in length, and for 90 minutes in the usual situation.

SCLC has reduced the risk of thermal cracks, compressive strength of at least 17 MPa, corrosion resistance of sulfates and chlorides, and freezing and thawing according to the standard compared to ordinary concrete [32,33]. Friction between solid particles (coarse-aggregated, fine-aggregated, and all forms of powders) must be decreased for concrete to deform correctly [28]. For reducing friction between solid particles, using spherical pozzolans, such as volcanic ash, is efficient. It should be emphasized, however, that lowering the friction between aggregates and powders reduced segregation resistance [34]. The mixing design for SCLC should be set in a way that satisfies all the properties of fresh and hardened concrete. A mixing design can be classified as a self-compacting concrete group when it fully provides the filling ability, the ability to pass through barriers, and the resistance to segregation. SCC has the following characteristics: 1- Powder to water volume ratio of 0.85-1.1, 2- Powder content, 400-600 kg/m^3, 3- Coarse aggregate content of typically 28-35% by volume of the mixture, 4- the amount of aggregates, in general, should balance the volume of other major components. 5- The water-to-cement ratio is chosen based on the EFNARC standard 2002 circumstances [32]. The difference in water content of the aggregates compared to the mixing design allowed within the specified limits. Naturally, the viscosity and ductility of concrete additives are efficiency tools for compensating for variations in aggregate size and water content [35,36]. A considerable quantity of powder material is used in SCLC mixes to retain the viscosity and flow qualities of fresh concrete. Limestone powder, silica fume, and other powder ingredients are often used in SCC mixtures since a significant quantity of cement increases costs and creates a lot of heat [37].

In this study, the mechanical characteristics of SCLC have been examined using pumice Taftan lightweight aggregate and various percentages of metakaolin. For this purpose, 135 concrete specimens containing 0, 5, 10, 15, and 20% metakaolin have been constructed. The experiments have been performed in two phases of fresh and hardened concrete. For the fresh concrete, V-Funnel, L-Box, Slump flow, and T_{50} slump tests have been executed. For the hardened concrete, the compressive strength test (BS 1881 Part 116), the tensile strength test (ASTM C496), and the flexural strength test (ASTM C78) have been performed on the SCLC specimens. Sistan Portland cement type 2, Zahedan sand, Taftan pumice, Indian metakaolin, Qom stone powder, silica fume, and superplasticizer have been used in the specimens. Five concrete designs containing metakaolin have been constructed, processed, and kept in the control environment (Zahedan drinking water) for 7, 14, and 28 days.

2. Testing schedule

2.1. The utilized substances

2.1.1. The utilized aggregate materials

In the attending research, Taftan pumice and Lar mine sand have been utilized as coarse aggregate and fine aggregate, respectively. The peak size of the utilized coarse-grained substances is 9.5 mm, and its size bounds are 2.36-9.5 mm. The fine-grains size employed is 0.4-75 mm. Tables 3 and 4 show the remaining and passing materials from the sieves, and Figures 2 and 3 show grading curves of pumice and sand, respectively. From pumice and sand, materials were used in a saturated surface dry (SSD) in such a way that they were saturated in water for 24 hours, and then they were taken out of the water, and their surface moisture was dried. 24-hour water absorption of pumice is 43%, and sand is 2.8%. The specific gravity of pumice is 473 kg/m^3 based on (ASTM C330) standard.

Pumice as coarse aggregate is an igneous aluminum silicate with a light tint, cellular structure, and many holes, which are filled by nearby glass components. Pumice is frequently employed in the construction sector because of its unique characteristics, which include low specific gravity, cell structure, lightweight, sound and heat insulation, and excellent abrasion resistance. Pumice has a density of around 2.6 g/cm^3 when powdered and about 1-1.5 g/cm^3 when crushed into 1-16 mm aggregates. Pumice aggregates have a porosity of up to 85%. Thus, air makes up 85% of its volume, while hard substance makes up the remaining 15%. This mineral is thermally insulating and has a melting point (about 1345^{o}C). In addition, this mineral does not change much in its shape and volume up to a temperature of 760° C. These characteristics have caused this mineral to prevent the destruction of buildings due to overheating the metal frame during a fire. Therefore, the usage of this mineral is economical and does not impose additional costs [33]. Table 1 shows the findings of the chemical compositions of Taftan pumice pozzolan [35]. In addition, Figure 1 depicts the pumice-grading curve in this research and the allowable range according to (ASTM C330). Also, pumice-grading characteristics, suchlike the remaining values and passing through the sieves, have been demonstrated in Table 2. Taftan pumice pozzolan has been illustrated in Figure 2.

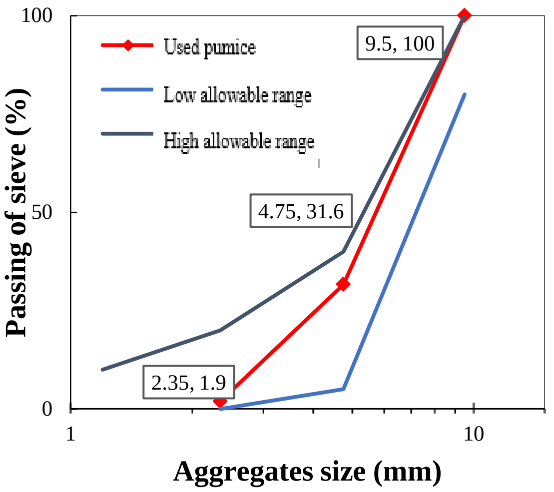


Fig. 1. Pumice-grading curve and allowable range according to (ASTM C330).

The Lar mine materials as fine aggregate utilized in this research had a 24-hour water absorption of 2.8% and specific gravity of 1400 kg/m^3. The sand-grading curve in this research and the allowable range according to (ASTM C33) have been illustrated in Figure 4. Also, sand-grading characteristics, suchlike the remaining values and passing through the sieves, have been demonstrated in Table 3.

2.1.2. Metakaolin

In the current project, metakaolin has been utilized as an additive instead of cement. Metakaolin is built by calcinating pure kaolin (mineral clay) at a temperature of (650-800) °C during regulated heat treatment. This heat breaks the crystalline structure of the kaolin and changes it to amorphous aluminum silicate (A2S). Metakaolin is a highly active pozzolan with a large specific surface area that may be utilized to substitute an amount of the volume of cement as an adhesive. Metakaolin is transformed into hydrated calcium silicate during the pozzolanic reaction with hydrated lime when employed in concrete. Metakaolin particles are around ten times smaller than cement particles, making concrete denser and impervious to water when used in construction. Adding metakaolin to concrete improves its strength to chemic assaults, sulfates, and glaciated and melting processes. Further, metakaolin can improve the mechanical characteristics of concrete, like compressive strength, short-term properties, and flexural strength. According to the (ASTM C618) standard, metakaolin is an amorphous white aluminum silicate with pozzolanic capabilities and has classed as Class N pozzolans (raw or calcined natural pozzolans). Metakaolin has been illustrated in Figure 3 as an example. Like other pozzolans, metakaolin interacts with calcium hydroxide to generate hydrated cement and calcium silicate hydrated (C-S-H). The most prevalent ingredients of metakaolin are SiO_2 and AL_2O_3. Metakaolin has found in the center of the Pozzolan pyramid [3–6]. The metakaolin's chemical components have been demonstrated in Table 4 [5].

Fig. 2. Taftan pumice pozzolan.

Fig. 3. Metakaolin.

2.1.3. Cement

The cement used in this research is modified Portland cement (type II) produced in the Sistan factory with a specific weight of 3150 kg/m^3, and a special surface area of 3159 cm^2/gr has been applied. The cement's physical and chemical compositions used in this study, which were received from the manufacturer, have been demonstrated in Table 5.

2.1.4. Stone powder

In this research, to control the viscosity of fresh concrete, Qom stone powder was utilized in about 60% by weight of cement with a specific weight of 2700 kg/m^3 and a specific surface of particles of 500-550 kg/m^2. The chemical compositions of the stone powder utilized in the current study have been demonstrated in Table 6 based on the information received from the manufacturer.

2.1.5. Superplasticizer

The deformability of concrete is strongly connected to the ductility of concrete mortar and may be enhanced by using superplasticizers. While adding the value of water used diminishes the yield stress and density factors. The superplasticizers diminish viscosity while improving flowability. Consequently, concrete with high liquefaction can be produced without offering considerable uniformity. Furthermore, decreasing the water-to-powder ratio w/p of cement paste may restrict its deformability. Powder components, such as cementitious materials and fillers, have been utilized to balanced the w/p ratio to produce an appropriate flexibility and deformation rate [36]. In this research, the POWER PlAST-RM Super plasticizer produced by Abadgaran Chemical Industry Factory has been utilized with a concentration of 2.5% of cement weight.

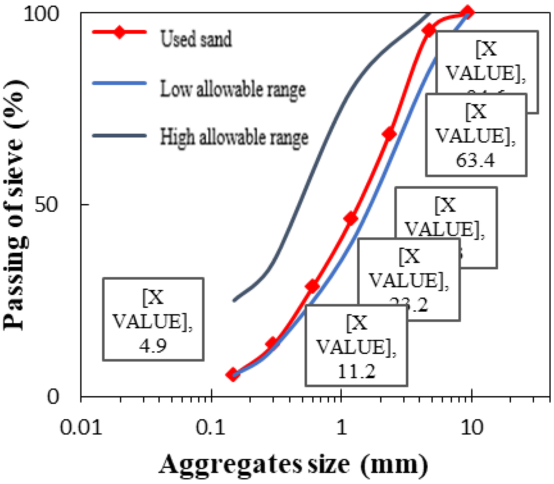


Fig. 4. Sand-grading curve and allowable range according to (ASTM C33).

2.1.6. Silica fume

Silica fume enhances the rheological attributes of fresh concrete and the quality of hard concrete by increasing compressive strength and decreasing water absorption. It is beneficial for producing high-strength concretes without vibration or additional energy for compaction. In this study, silica fume containing 10% by weight of cement has been employed.

2.2. Experiment procedure

At first, three initial mixing schemes were created by the volumetric method. The materials used in the initial experimental designs are shown in Table 7. Scheme A was chosen as the specimen-mixing scheme owing to the lower cement consumption. Then five mixing schemes from type A were created and evaluated by adding 0, 5, 10, 15, and 20% metakaolin. The main mixing scheme is shown in Table 8. Five concrete designs from type A containing metakaolin were constructed, processed, and kept in the control environment (Zahedan drinking water) for 7, 14, and 28 days. The specimens were produced with Sistan-type 2 cement, Zahedan sand, Taftan pumice, Indian metakaolin, Qom stone powder, silica fume, and superplasticizer. The 135 concrete specimens from type A were constructed contained 0, 5, 10, 15, and 20% metakaolin. The SCLC containing 5, 10, 15, and 20% metakaolin have been called SCLCCM-5, SCLCCM-10, SCLCCM-15, and SCLCCM-20 as mixing codes, respectively. The SCLC without metakaolin is called SCLCWM. Then the experiments were performed in two phases fresh and hardened concrete. For fresh concrete, V-Funnel, L-Box, Slump flow, and T_{50} slump tests were conducted. For hardened concrete, the compressive strength test (BS 1881 Part 116), the tensile strength test (ASTM C496), and the flexural strength test (ASTM C78) were performed on the SCLC specimens. Sampling was carried out using cubic molds with dimensions of 150×150×150 mm, cylindrical molds with dimensions of 150×300 mm, and cubic molds with dimensions of 150×150×750 mm after an appropriate mixing scheme for SCLC was developed. One day after making the samples, entire samples were pulled from the molds and placed in a plunge pond with ordinary water at a temperature of (20-25) °C (control environment), where they were investigated after 7, 14, and 28 days.

Table 1. Chemical compositions of Taftan pumice pozzolan [35].

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Cl	K_2O	Na_2O
Pumice (%)	61.57	18.00	4.93	6.69	2.63	0.14	0.04	1.95	1.65

Table 2. Characteristics of pumice-grading.

Sieve numbe	Sieve size (mm	Remaining weight (gr)	Remaining (%)	Volume passing (%)
		One sieve		
3/8	9.5	0	0	100
4	4.75	684	68.4	31.6
8	2.36	297	98.1	1.9
Tray	-	19	-	0.00
Total weight		1000	166.5	-

Table 3. Characteristics of sand-grading.

Sieve number	**Sieve size (mm)**	**Remaining weight (gr)**		**Remaining (%)**	**Volume passing (%)**
		All sieve	One sieve		
4	4.75	54	54	5.40	94.60
8	2.35	366	312	36.60	63.40
16	1.20	607	241	60.70	39.30
30	0.60	768	161	76.80	23.20
50	0.30	888	120	88.80	11.20
100	0.15	951	63	95.10	4.90
Tray	-	1000	49	-	0.00
Total weight		-	1000	363.4	-
fineness modulus ~ 3.63					

Table 4. Chemical compositions of metakaolin [5].

Chemical composition	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**K_2O**	**NaO_2**	**TiO_2**	**P_2O_5**	**SO_3**	**LOI**
Content in weight (%)	53.00	43.80	0.43	0.02	0.03	0.19	0.23	1.70	0.03	0.03	0.46

Table 5. Physical and chemical characteristics of cement.

	Physical		**Chemical analysis (%)**						**Bogue composition (%)**			
	Specific gravity (kg/m^3)	Blaine (cm^2/g)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	C_4A	C_3A	C_3S	C_2S
Content	3150	3159	21.38	5.37	3.84	62.7	1.69	2.48	11.7	7.73	44.1	27.66

Table 6. Chemical compositions of stone powder.

Chemical composition	**CaO**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**SO_3**	**NaO_2**	**Other composition**
Content (%)	71.39	8.10	2.30	0.80	0.88	0.26	0.14	16.13

Table 7. Initial mixing schemes (kg/m^3).

Mixing code	**Cement**	**Silica fume**	**Stone powder**	**Water**	**W/C**	**Superplasticizer**	**Sand**	**Pumice**	**Volume weight**
A	450	45	250	158	0.35	11	725	308	1947
B	475	45	225	166	0.35	12	686	291	1900
C	500	45	200	175	0.35	13	663	282	1878

Table 8. Main mixing scheme (kg/m^3).

Mixing code	Cement	Silica fume	Stone powder	Metakaolin	Water	W/C	Superplasticizer	Sand	Pumice
SCLCWM	450	45	250	-	158	0.35	11	725	308
SCLCCM-5	427.5	45	250	22.5	158	0.35	11	725	308
SCLCCM-10	405	45	250	45	158	0.35	11	725	308
SCLCCM-15	382.5	45	250	67.5	158	0.35	11	725	308
SCLCCM-20	360	45	250	90	158	0.35	11	725	308

2.3. Fresh concrete experiments

Concrete is composed of heterogeneous and complex materials. Fresh concrete has properties that have a direct and significant impact on the final quality of concrete, cost, resistance, and durability [38]. The characteristics of viscosity, permeability, flowability, and enhanced detachment strength of concrete are decisive in determining the filling properties and stability of fresh SCLC. Flowability and viscosity of fresh concrete can be gauged by the T_{50} slump and V-Funnel tests, respectively. The current research, the Slump test, T_{50} slump, L-Box, and V-Funnel experiments were performed to check fluidity, viscosity, and detachment in concrete samples. Therefore, slump flow, slump T_{50}, L-Box, and V-Funnel tests based on the EFNARC 2002 standard [27] were utilized to distinguish the characteristics of fresh concrete in this research. The desirable performance of fresh SCLC containing pumice aggregate is acquired using fresh concrete tests. All experiments were accomplished at 20°C. The slump test appraises the filling ability of SCLC.

The method of performing the T_{50} slump test is that first, the 900×900 mm test plate is completely cleaned, and the cone is placed on it and in the center of the plate, whose diameter is 200 mm. Then, the inside of the cone is filled with the desired concrete perpendicular to the plane, and it is pulled upwards with a continuous movement. When the concrete reaches a diameter of 500 mm, it is recorded. The average diameter is measured and recorded by measuring the diameter in two perpendicular directions. This is the size of the Slump flow in millimeters. The L-Box test expresses the concrete flowability and obstruction caused by rebar spacing. In this experiment, the standing part of the box, which has dimensions of 100×200×600 mm, is filled with about 14 liters of concrete. Then the valve behind the table of the reinforcements is pulled up so that the concrete passes through the intervals of the reinforcements and flows in the horizontal part of the box. After the concrete settles, the values of H_2 and H_1 are gauged, and the ratio of these two, H_2/H_1, is suggested as a criterion for measuring the flowability of SCLC. The device of the L-Box test has been illustrated in Figure 5.

Fig. 5. Device of L-Box test.

The V-Funnel test is done to demarcate the power of concrete to change the flow direction and pass through reinforcement and bound sections without segregating and obstructing the flow. The V-Funnel device should be placed in a flat and horizontal place during testing, and then 12-14 liters of concrete should be poured into it. After the concrete surface is filled, the lower valve of the machine is pulled out with a 10-second pause. From this moment, the time is measured until the moment when the entire concrete is emptied. This time is indicated by T_v. Once again, we fill the funnel with concrete and leave it for 5 minutes, open the valve, and measure the time when the concrete leaves the funnel.

Fig. 6. Device of V-Funnel test.

The device of the V-Funnel test has been illustrated in Figure 6.

2.4. Hardened concrete experiments

This research was done in two phases. In the first phase, suitable mixing designs for SCLC were obtained, and in the second phase, various tests were performed. One day after the concrete was constructed, the entire specimens were pulled from the mold and then transferred to the processing pond with ordinary water at a temperature of 20-25^{o} (control environment); after processing for 7, 14, and 28-day, they were taken out of the pond and have been tested. Some specimens in the holding basin are shown in Figure 7.

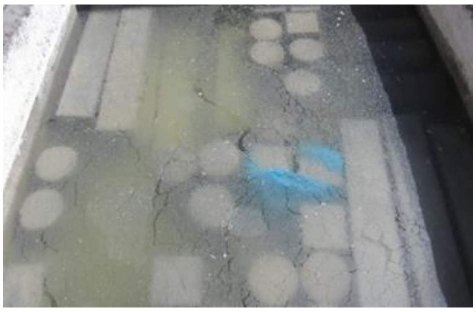


Fig. 7. Some specimens in the holding.

Fig. 8. Compressive strength test.

In the attending research, the compressive strength experiments based on (BS 1881 Part 116) standard were done on cubic specimens with dimensions of 150×150×150 mm. The number of specimens to test the compressive strength of 7, 14, and 28 days with various percentages of metakaolin in storage situations is 45. Figure 8 indicates a broken specimen under a compressive strength experiment.

Flexural strength tests based on (ASTM C78) standard were done on specimens with the dimensions of 150×150×750 mm. The number of specimens for 7, 14, and 28-day flexural strength tests with various percentages of metakaolin in storage conditions is 45. Figure 9 indicates a ruptured specimen under a flexural strength experiment.

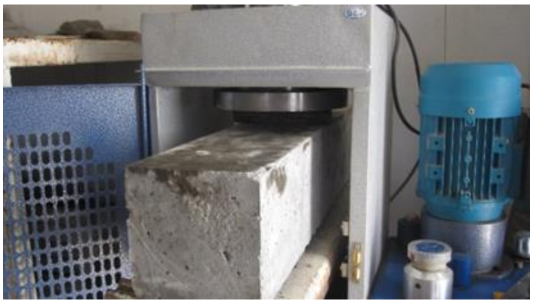


Fig. 9. Flexural strength test.

Tensile strength tests based on (ASTM C496) standard were done on cylindrical specimens with dimensions of 150×300 mm. The number of specimens to test the splitting tensile strength of 7, 14, and 28-day with various percentages of metakaolin in storage conditions is 45. Figure 10 indicates a broken specimen under the splitting tensile strength test.

Fig. 10. Splitting tensile Strength test.

Table 9. The standard deviation of compressive and flexural strength tests.

Category		SCLCWM	SCLCCM-5	SCLCCM-10	SCLCCM-15	SCLCCM-20
Compressive strength	SD-7 (%)	14.35	12.65	18.21	15.53	11.39
	SD-14 (%)	8.77	19.14	16.38	13.25	12.36
	SD-28 (%)	14.64	13.81	12.54	10.42	16.22
Flexural strength	SD-7 (%)	12.05	16.63	17.11	14.55	16.78
	SD-14 (%)	18.33	14.19	12.97	13.38	15.78
	SD-28 (%)	11.75	13.09	15.46	11.37	14.27
Tensile strength	SD-7 (%)	13.15	12.12	11.86	17.94	16.58
	SD-14 (%)	19.58	15.73	16.49	16.44	17.17
	SD-28 (%)	18.46	13.60	16.22	14.08	18.70

The standard deviation (SD) of the categories tested in this research have been shown in Table 9. The classification has been done according to the added percentages of metakaolin at different ages and the type of hardened concrete test. Equation 1 has been used to obtain the standard deviation presented in Table 9. In addition, the standard deviation of 20% has been considered as the acceptance criterion for the samples.

$$SD=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2} \qquad (1)$$

Where, n, x_i, and $\bar{x}$ are the number of samples in each category, the value obtained in each experiment corresponding to the same category, and the average value of each category, respectively.

3. Research results

3.1. Fresh concrete phase

The fresh SCLC tests have been performed after the concrete is constructed and before setting. Then its results have been inspected at this stage. In this research, the EFNARC standard 2002 was used for evaluating the fresh SCLC. The characteristics of viscosity, permeability, flowability, and enhanced detachment strength of concrete are decisive to determining the filling properties and stability of fresh SCLC. Thus, Characteristics such as flowability and viscosity were determined by T_{50} and V-Funnel tests. The slump test, T_{50} slump test, V-Funnel, and L-Box test were performed for flowability, viscosity, and segregation of concrete specimens the results; have been presented in Table 10. In addition, EFNARC standard 2002 recommends slump test values in three categories SF1 (550-650) mm for lightly reinforcement structures, SF2 (660-750) mm for typical concrete applications, and SF3 (760-850) mm for high-compactness of rebar places.

All the mixing designs containing metakaolin in this test are within the allowable spectrum of SF2. According to Figure 11 and based on the EFNARC standard 2002, the initial mixing designs are in the range of SF2 and VS2/VF2. The experiment results of fresh concrete for initial mixing schemes have been demonstrated in Table 10.

Table 10. Results of fresh concrete tests for initial mixing schemes

Mixing code	Slump flow (mm)	T_{50} (Sec)	L-Box	V-Funnel
A	660	4	0.82	11
B	690	5	0.84	13
C	710	5	0.84	13

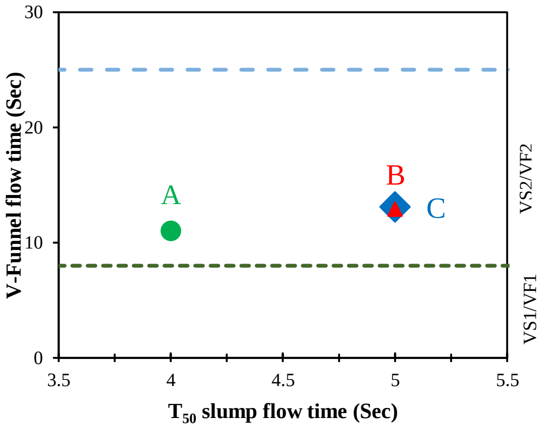


Fig. 11. Viscosity classes for initial mixing schemes.

3.2. Hardened concrete phase

3.2.1. Compressive strength test

Figure 12 has shown the results of compressive strength tests for SCLC at the ages of 7, 14, and 28 days. Figure 13 has shown a variation in compressive strength (VCS) at different metakaolin percentages for SCLC at the ages of 7, 14, and 28 days. Furthermore, the compressive strength of specimens containing metakaolin at the ages of 7, 14, and 28 days have shown in Table 11. As shown in Figure 14, increasing the metakaolin advanced the compressive strength of the specimens, and this rise in strength persisted until the addition of 15% metakaolin, after which the downward tendency to takes itself.

In addition, when compared to SCLCWM, the compressive strength SCLCCM-5 demonstrated a 7-day improvement in strength similar to 13%. Compared to SCLCWM, the compressive strength of the 14-day specimens of SCLCCM-5 rose by 10%, while the compressive strength of the 28-day specimens increased by 7%.

Compared to SCLCWM, the compressive strength SCLCCM-10 demonstrated a 28% improvement in strength age of 7-day. Compared to SCLCWM, the compressive strength of the 14-day specimens of SCLCCM-10 increased by 22%, while the compressive strength of the 28-day specimens increased by 17%.
Compared to SCLCWM, the compressive strength SCLCCM-15 demonstrated a 39% improvement in strength age of 7-day. Compared to SCLCWM, the compressive strength of the 14-day specimens of SCLCCM-15 increased by 31%, while the compressive strength of the 28-day specimens increased by 26%.

Compared to SCLCWM, the compressive strength SCLCCM-20 demonstrated a 30% improvement in strength age of 7-day. The 14-day specimens of SCLCCM-20 have a compressive strength that is 25% greater than SCLCWM, while the 28-day specimens have a compressive strength that is 19% higher.
It has been shown that raising metakaolin to 15% boosted concrete strength while increasing it to 20% slowed the process of growing strength. This indicates that 15% metakaolin is the best quantity to consume.

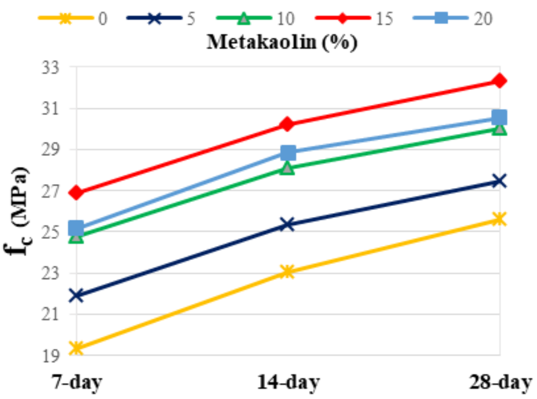


Fig. 12. VCS at different ages.

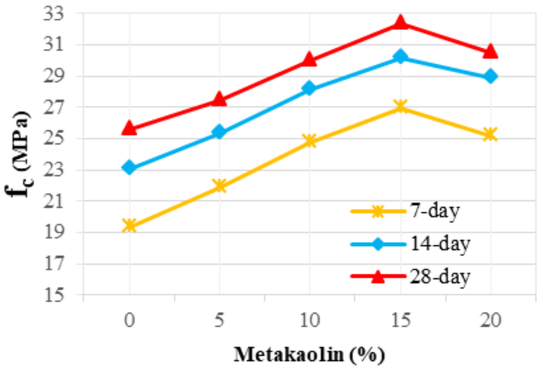
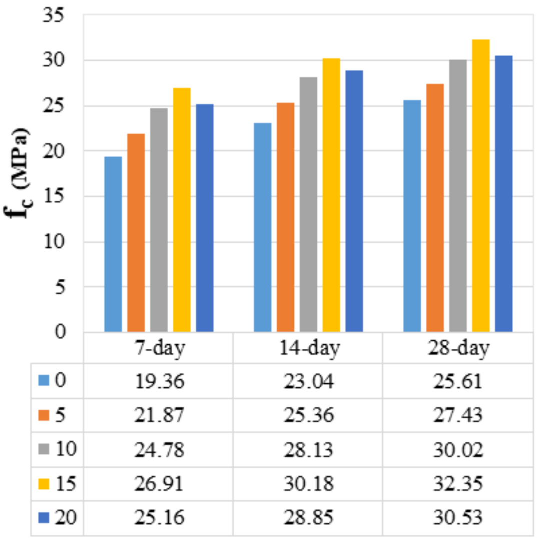


Fig. 13. VCS at different metakaolin percentages.



	7-day	14-day	28-day
0	19.36	23.04	25.61
5	21.87	25.36	27.43
10	24.78	28.13	30.02
15	26.91	30.18	32.35
20	25.16	28.85	30.53

Table 11. VCS at various metakaolin percentages and different ages.

Researchers obtained the amount of 15% metakaolin to increase the compressive strength of concrete [7,26]. The results obtained in this study are consistent with the results of the researchers. Demirel et al. used pumice as light fine aggregate and obtained

18% metakaolin to increase compressive strength [25]. This difference shows the effect of the mixing design on the obtained metakaolin amounts.

A broken specimen in the compressive strength test has been illustrated in Figure 14.

Fig. 14. A broken specimen in compressive strength test.

3.2.2. Tensile strength test results

Figure 15 has shown the results of splitting tensile strength tests for SCLC at the ages of 7, 14, and 28 days. Figure 16 has shown variation of splitting tensile strength (VSTS) at different metakaolin percentages for SCLC at the ages of 7, 14, and 28 days. Furthermore, the values of splitting tensile strength of specimens containing metakaolin at the ages of 7, 14, and 28 days have shown in Table 12. As indicated in Figure 16, the splitting tensile strength of the specimens grew as the percentage of metakaolin was raised. This rise continued until the addition of 15% metakaolin, after which the downward tendency to takes itself.

In addition, compared to SCLCWM, the splitting tensile strength SCLCCM-5 demonstrated a 10% improvement in strength 7-day. The 14-day specimens of SCLCCM-5 have a tensile strength that is 7% greater than SCLCWM, and the 28-day specimens has a tensile strength that is 5% higher.

Compared to SCLCWM, the splitting tensile strength SCLCCM-10 demonstrated a 19% improvement in tensile strength age of 7 days. Compared to SCLCWM, the splitting tensile strength of the 14-day specimens of SCLCCM-10 rose by 12%, while the tensile strength of the 28-day models increased by 8%.

Compared to SCLCWM, the splitting tensile strength SCLCCM-15 demonstrated a 26% improvement in tensile strength age of 7days. Compared to SCLCWM, the splitting tensile strength of the 14-day specimens of SCLCCM-15 increased by 19%, while the tensile strength of the 28-day models increased by 14%.

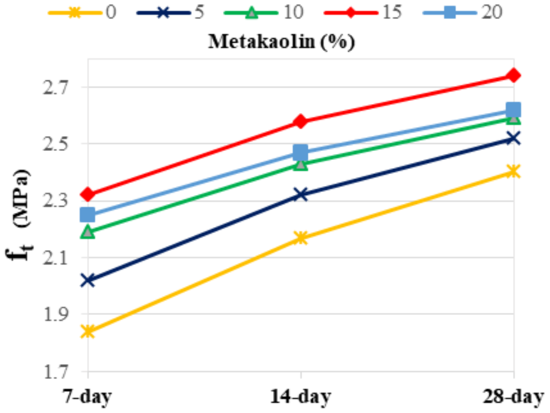


Fig. 15. VSTS at different ages.

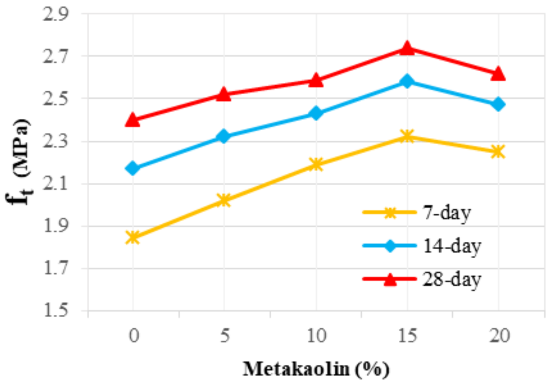
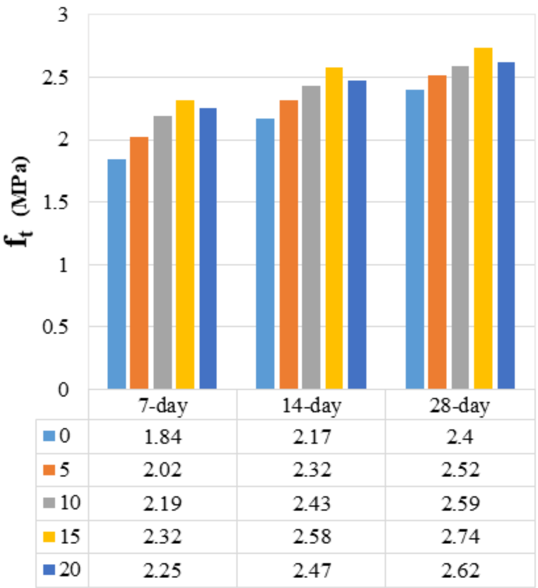


Fig. 16. VSTS at different metakaolin percentages.

Compared to SCLCWM, the splitting tensile strength SCLCCM-20 demonstrated a 7-day improvement in tensile strength similar to 22%. Compared to SCLCWM, the splitting tensile strength of the 14-day specimens of SCLCCM-20 rose by 14%, while the tensile strength of the 28-day models increased by 9%.



	7-day	14-day	28-day
■ 0	1.84	2.17	2.4
■ 5	2.02	2.32	2.52
■ 10	2.19	2.43	2.59
■ 15	2.32	2.58	2.74
■ 20	2.25	2.47	2.62

Table 12. VSTS at various metakaolin percentages and different ages.

It has been shown that adding metakaolin to 15% improved concrete strength while adding it amount 20% slowed the growing strength. This indicates that 15% metakaolin is the best quantity to consume. The best tensile strength results are reported for specimens with 15% metakaolin [7,26]. The results obtained in this study are consistent with the results of the researchers.

Fig. 17. A broken specimen in splitting tensile strength test.

A broken specimen in the splitting tensile strength test has been illustrated in Figure 17.

3.2.3. Flexural strength test results

Figure 18 has shown the results of the flexural strength tests for SCLC at the ages of 7, 14, and 28 days. Figure 19 has shown the variation of flexural strength (VFS) at different metakaolin percentages for SCLC at the ages of 7, 14, and 28 days. Furthermore, the values of the flexural strength of specimens containing metakaolin at the ages of 7, 14, and 28-day have shown in Table 13. As seen in Figure 19, the flexural strength of the specimens grew as the percentage of metakaolin was raised. This rise continued until the addition of 15% metakaolin, after which it declined with increasing metakaolin intake.

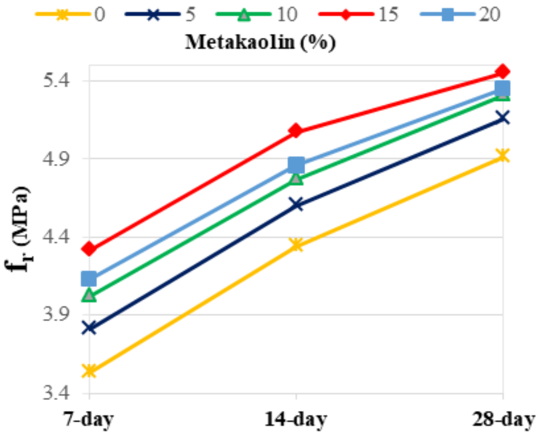


Fig. 18. VFS at different ages.

In addition, when compared to SCLCWM, the flexural strength SCLCCM-5 demonstrated an 8% improvement in the age of 7-day. In addition, Compared to SCLCWM, the flexural strength of the 14-day specimens of SCLCCM-5 was raised by 6%, and the flexural strength of the 28-day models were increased by 5%.

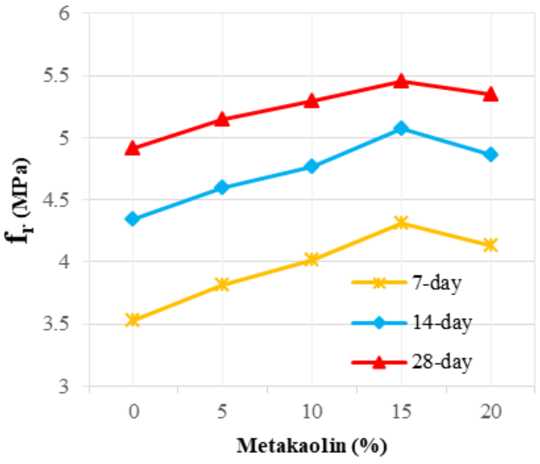
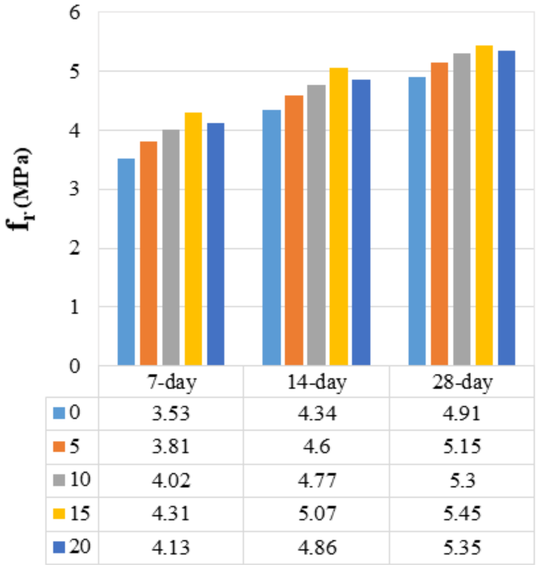


Fig. 19. VFS at different metakaolin percentages.

Table 13. VFS at various metakaolin percentages and different ages.



	7-day	14-day	28-day
0	3.53	4.34	4.91
5	3.81	4.6	5.15
10	4.02	4.77	5.3
15	4.31	5.07	5.45
20	4.13	4.86	5.35

Compared to SCLCWM, the flexural strength SCLCCM-10 demonstrated a 14% improvement at the age of 7-day. Compared to SCLCWM, the flexural strength of the 14-day specimens of SCLCCM-10 rose by 10%, while the flexural strength of the 28-day models increased by 8%.

Compared to SCLCWM, the flexural strength SCLCCM-15 demonstrated a 22% improvement at the age of 7-day. A 14-day specimen of SCLCCM-15 has a 17% greater flexural strength than SCLCWM, while the 28-day specimen has an 11% higher flexural strength.

Compared to SCLCWM, the flexural strength SCLCCM-20 demonstrated a 17% improvement in flexural strength age of 7-day. Compared to SCLCWM, the flexural strength of the 14-day specimens of SCLCCM-20 rose by 12%, while the flexural strength of the 28-day specimens increased by 9%.

It has been discovered that raising metakaolin by 15% increases the flexural strength of concrete while increasing it by 20% reduces the trend of rising strength. This indicates that 15% of metakaolin is the best intake. Fawzi et al. obtained the amount of 15% metakaolin for the greatest flexural strength [26]. The results obtained in this research are consistent with the results of the researchers.

Some specimens broken in this research under the flexural strength test have been illustrated in Figure 20.

Fig. 20. A broken specimen in splitting tensile strength test.

4. Discussion

Metakaolin raises the strength of concrete due to its high specific surface and very high pozzolanic activity. Because of this activity, the calcium hydroxide in the concrete is destroyed, and hydrated calcium silicate is produced. Hydrated calcium is considered the most significant strength factor of cement paste, which can fill the voids in concrete, especially in the transition region, and lead to improvement in the concrete's microstructure. Pozzolanic properties of pumice cause the production of hydrated calcium silicate which have an improving effect on the microstructure. At the same time, a part of metakaolin may remain free, in the concrete, due to a lack of sufficient lime; and directly cause the filling of voids in the microstructure. As it was observed, when metakaolin is added more than 15%, it reduces the mechanical properties of concrete. This problem is due to the filling of empty spaces of concrete with extra metakaolin. But smaller amounts will not have a destructive effect on concrete. Therefore, 15% of metakaolin has been extracted as the best strength effect on specimens containing pumice and metakaolin.

5. The suggested equations

Using the results obtained in the previous steps, relationships can be provided to evaluate the mechanical properties. Therefore, two equations for estimating the flexural and splitting tensile strength of SCLC in terms of 28-day compressive strength have been presented, which shown in Figures 21 and 22. However, linear Equations 2 and 3 can indicate the flexural and splitting tensile strength SCLCs in terms of compressive strength. In these equations, the error has occurred to an acceptable extent.

$$f_{r-28} = 0.0775 f_{c-28} + 2.969 \qquad R^2 = 0.9667 \tag{2}$$

$$f_{t-28} = 0.0464 f_{c-28} + 1.219 \qquad R^2 = 0.9688 \tag{3}$$

Where $f_{r\text{-}28}$, $f_{t\text{-}28}$, and $f_{c\text{-}28}$ are the modulus of rupture or flexural strength, splitting tensile strength and compressive strength 28-day, respectively.

Figures 23, 24, and 25 have been illustrated the compressive, tensile, and flexural strengths of SCLCs in terms of metakaolin percentage at the age of 28 days, respectively. Finally, considering Figures 23, 24 and 25, formulas 4, 5, and 6 (with admissible R-squared) have been proposed to estimate the compressive, tensile, and flexural strengths of 28-day SCLC containing metakaolin, respectively.

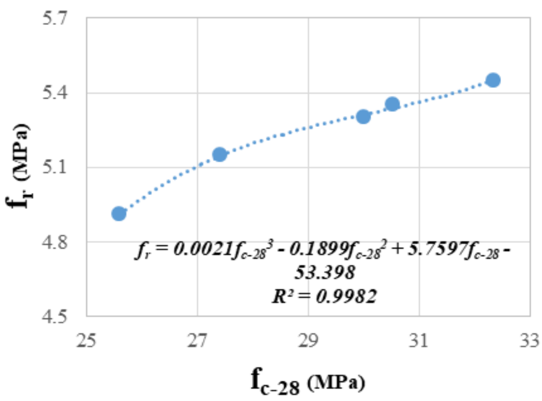


Fig. 21. fr in terms of fc-28.

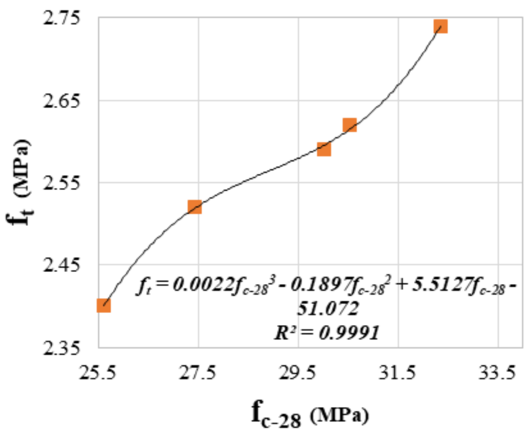


Fig. 22. ft in terms of fc-28.

$$f_{c-28} = -0.0033M^3 + 0.0769M^2 + 0.0209M + 25.651 \qquad R^2 = 0.9959 \tag{4}$$

$$f_{t-28} = -0.0001M^3 + 0.0033M^2 + 0.0045M + 2.4069 \qquad R^2 = 0.9479 \tag{5}$$

$$f_{r-28} = -0.0001M^3 + 0.0013M^2 + 0.0395M + 4.9149 \qquad R^2 = 0.9906 \tag{6}$$

Where, *M* shows the percentage of metakaolin consumption in SCLC.

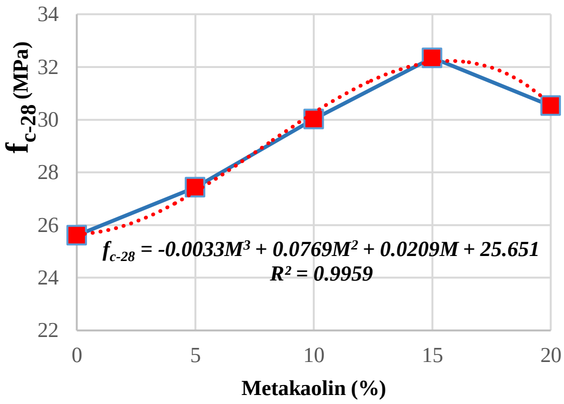


Fig. 23. f_{c-28} in terms of metakaolin percentage.

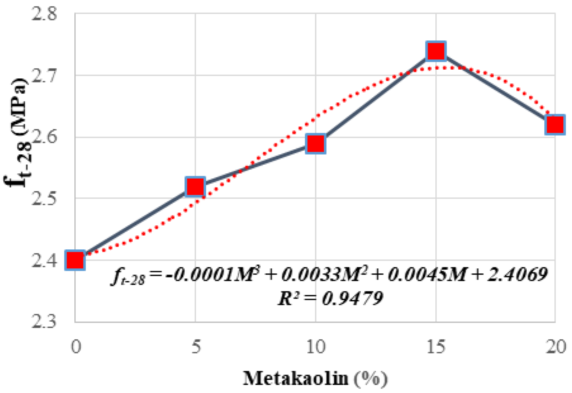


Fig. 24. ft-28 in terms of metakaolin percentage.

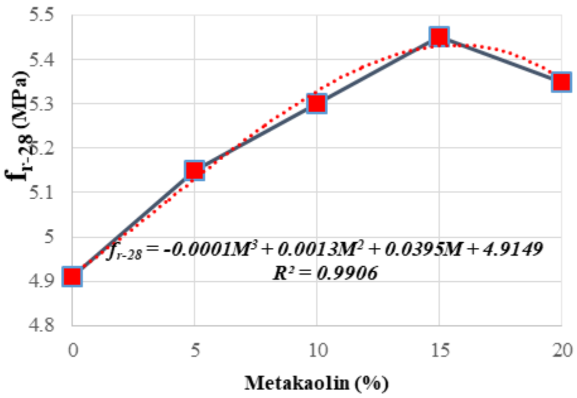


Fig. 25. fr-28 in terms of metakaolin percentage.

6. Conclusions

Due to its high pozzolanic activity, metakaolin increases the strength of concrete and produces hydrated calcium silicate. The pozzolanic properties of pumice also cause the production of hydrated calcium silicate, which has an improving effect on the concrete microstructure. At the same time, a part of metakaolin may remain in concrete due to the lack of free lime and fill the empty spaces in the concrete microstructure. In the present research, it was observed that the mixture with 20% metakaolin significantly reduces the strength of concrete. However, adding 15% of metakaolin increases the strength of concrete. Therefore, excess metakaolin can reduce the strength of concrete.

- According to the results from the fresh concrete slump, the class of concrete is SF2. SF2 concrete class is suitable for many standard concrete pouring applications. If there is no need for the specific use of concrete, it is recommended to adjust the amount of concrete Slump flow in this range.
- The L-Box test was used to measure the passability of self-compacting lightweight concrete. The obtained value of 0.82 indicates the proper filling ability of self-compacting lightweight concrete.
- According to the obtained value of 11 sec in the V-Funnel test, the concrete class is VS2-VF2. In this class, the pressure on the molds is reduced, and the concrete segregation is also reduced.

Finally, the following results can be summarized based on observations and experiments in this research:

- Compressive strength tests show that by adding a percentage of metakaolin instead of cement, the compressive strength of lightweight concrete containing pumice and metakaolin increases. The most significant increase in compressive strength is in light concrete specimens containing 15% metakaolin, and by adding more than this amount, the compressive strength decreases. Therefore, the best specimens constructed in terms of compressive strength are SCLCCM-15 specimens.
- Splitting tensile strength tests show that by adding a percentage of metakaolin instead of cement, the tensile strength of light concrete containing pumice and metakaolin increases. The most significant increase in tensile strength is in lightweight concrete specimens containing 15% metakaolin, and by adding more than this amount, the tensile strength decreases. Therefore, the best specimens constructed for splitting tensile strength are SCLCCM-15 specimens.
- Flexural strength tests show that by adding a percentage of metakaolin instead of cement, the flexural strength of lightweight concrete containing pumice and metakaolin increases. The most significant increase in flexural strength is in light concrete specimens containing 15% metakaolin, and by

adding more than this amount, the flexural strength decreases. Therefore, the best specimens constructed regarding flexural strength are SCLCCM-15 specimens.

As a final note, it can be expressed that in terms of mechanical properties, SCLCCM-15, which is constructed with lightweight pumice aggregate, is the most robust concrete in the self-compacting lightweight concrete group.

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