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Application of light concrete balls as floatation balls to reduce evaporation from free water surfaces

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Abstract
Evaporation is a significant climatic phenomenon, particularly in arid and semi-arid regions, where it contributes to considerable water loss from open water bodies such as reservoirs, dams, and agricultural water storage ponds. Efficient management of evaporation is essential to conserve water resources and enhance irrigation sustainability. Although various methods have been proposed to reduce surface water loss, economic feasibility and ease of application remain key factors in their adoption. This study investigates an affordable and practical solution by employing floating cement balls made from low-cost and locally available materials to minimize evaporation from open water surfaces. To evaluate evaporation rates, several empirical models were tested under the climatic conditions of the Zayandeh Rood Dam reservoir. Among them, the Linacre, Ivanov, and DeBruin methods were identified as the most suitable for estimating daily and monthly evaporation in the study area. Additionally, laboratory experiments were conducted using different types of floating concrete balls. The results indicated that floating balls made of perlite, Lika-4-10, and Lika-2-4 reduced evaporation from the tank surface by 33.9, 38.5, and 42.7 percent, respectively. Therefore, Leca 2-4 concrete balls were the most effective, reducing evaporation compared to the uncovered surface. The outcomes of this research suggest that the proposed method offers a cost-effective and scalable approach for reducing evaporation losses, particularly in agricultural ponds and small-scale reservoirs in water-scarce regions.

Keywords: Water losses, Floating balls, Leca, Reservoir
Article Type: Research Article

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1. Introduction

Although water occupies more than 70% of the Earth's surface, less than 1% of this water is available and suitable for drinking. Besides that, population growth, pollution of water resources, climate change, and global warming are putting pressure on the Earth's available water resources; therefore, the importance and value of water in many countries all around the world with an arid or semi-arid climate have increased significantly over recent years. Iran, as one of the countries with a large area of arid and semi-arid climate, is struggling with the problem of a lack of water resources. In the world, especially in the Middle East, climate change and global warming lead to the development of droughts, and this change leads to a heterogeneous distribution of rainfall (Al-Awadhi et al. 2014). According to the above, it is clear that evaporation is one of the most important environmental processes that can hurt the quality and quantity of water available for industrial, agricultural, and household uses; therefore, evaporation losses have become a major challenge for the efficiency of water storage and supply in the world. Many efforts to decrease evaporation from water reservoirs and surfaces started in the 1960s using monolayer molecular films as an impermeable barrier for the water surface (Alvarez et al. 2006). Many studies have been done to reduce evaporation in different techniques, which can be divided into three general categories. The first category is physical methods such as floating covers, which are subdivided into continuous covers, floating sheets (Shalaby et al. 2021); or modular covers, floating objects (Shalaby et al. 2024); suspended covers, which are subdivided into Shade cloth (Alvarez et al. 2006; Martínez Álvarez et al. 2010); photovoltaic system (Majumder et al. 2021), and injection of air bubbles (Helfer 2012). Physical covers are floating or suspended covers that reduce evaporation by decreasing wind speed and radiation load (Zhang et al. 2010). Floating covers generally fall into two categories: 1. Continuous covers, and 2. Modular covers. Continuous covers are typically made from polystyrene (Craig et al., 2005). However, these covers can hinder the transmission of light and air to the water and may adversely affect water ecology and quality (Baradei & Sadeq, 2020; Rezazadeh et al., 2020). The second category is chemical methods, such as mono-layers and polyacrylamides, which form an invisible film that can be used to cover a reservoir and block evaporation (Saggai et al. 2016). The last one is biological methods such as floating aquatic plants (Youssef and Khodzinskaya 2019), wind-breakers (Hashemi Monfared et al. 2019; Hipsey et al. 2004, Helfer et al. 2009), and palm fronds (Alam and AlShaikh 2013; AlHassoun et al. 2011; Elsebaie et al. 2017). Floating covers include modular and flat sheet covers that float on the water surface. They reflect a proportion of the incoming solar radiation and act as physical barriers to the passage of water vapor both vertically and horizontally. Hou et al. (2018) also believe that floating balls with arc structures are more suitable as an anti-evaporation material. The first large-area floating ball coverage test in China was carried out using high-density polyethylene (HDPE) floating balls, and the annual water saving rate per unit area of water was 64.21–70.96%. A physical floating cover mainly prevents evaporation by blocking the transmission of solar radiation and reflecting a proportion of the incoming solar radiation. The anti-evaporation effect is related to the material, shape, coverage rate, and other factors of the cover. Shalaby et al. (2024) suggested that farmland irrigation reservoirs should be covered with plastic or foam sheets to gain the maximum evaporation suppression efficiency (96%) in the anti-evaporation test. However, in multipurpose reservoirs, the impact of such projects on the ecological environment is very important. It was recommended to use white inflatable PE balls to cover reservoir surfaces, but only 90 mm diameter floating balls were used for the test. Shalaby et al. (2021) investigated the performance of white foam sheets at 91% and 100% coverage percentage, plastic sheets at 91% and 100% coverage percentage, and white balls at 91% coverage percentage. Results showed that the full coverage of the water surface reduced evaporation by 96.0%, but in multi-purpose reservoirs, ecological considerations are more essential; thus, white-balls with a 91% coverage percentage are recommended. Jajin et al. (Jajin et al. 2022) by using hydrophobic bentonite investigated the reduction of water evaporation from water surfaces, on a laboratory scale, and in field conditions. Their results demonstrated that the hydrophobic bentonite efficiency under laboratory conditions was similar to that of hexadecanol and prevented water evaporation by 36%. However, under field conditions, hydrophobic bentonite worked better than hexadecanol by an efficiency of 40%. Wang et al. (2023) used five types of solid expanded polystyrene (EPS) to make floating balls with different diameters of 10 mm, 40 mm, 80 mm, 120 mm, and 150 mm and used them to study the evaporation suppression efficiency (ESE) of EPS floating balls on the evaporation of reservoir water surfaces in arid areas of China. The most prominent result of this research was that the ESE of floating balls with a diameter of 40 mm was the highest, at 76.31%. Benjaoran et al. (2023) investigated the effect of using drinking-water bottles to cover the water surface to reduce the loss of water in the reservoir. Results showed that the coverage area at 75% with the free-floating pattern will give an optimum reduction, and the best average Evaporation Suppression Efficiency was obtained, equal to 63.3%. As mentioned, millions of cubic meters of water evaporate from the soil and surface of water reservoirs annually and become unavailable, so accurate estimation of evaporation is essential in water resources planning. Therefore, determining the most appropriate model for estimating evaporation that has the least difference with the measurement results is essential. Also, despite abundant theoretical information on evaporation and how to control it, little practical work has been done in the field of evaporation control. For this reason, fundamental measures must be taken to use new ways to reduce evaporation in the country, especially in arid and semi-arid regions. One way to prevent evaporation from the surfaces of water reservoirs is to use floating covers. In this study, three different types of lightweight concrete are used and placed as floating balls on the surface of free reservoirs, and their performance will be examined. Based on previous research, the objectives of this research are:

1- Determining the best model for calculating the evaporation of the Zayandeh Rood basin.

2- Provide an inexpensive physical method, floating balls made of lightweight concrete, to reduce evaporation from the free surface of tanks.

2. Materials and Methods

In this research, at first, meteorological statistics and information from the Meteorological Organization were used to estimate the evaporation rate of the Zayandeh-Rood dam station. To estimate the evaporation rate of Zayandeh-Rood Dam using different methods, data related to meteorological variables including daily average air temperature (degrees Celsius), daily average relative humidity (percentage), monthly average wind speed (meters per second), and daily evaporation from the basin for a 16-year statistical period (2003-2019) were received from the Isfahan Regional Water Organization. On the other hand, in addition to the aforementioned meteorological parameters, other required meteorological variables, including sunshine hours and daily average wind speed (meters per second) for a 16-year statistical period (2003-2019), were received from the Meteorological Organization. Evaporation estimation was done by the methods of Meyer (Meyer 1915), Penman (Fritschen and Gay 1979), Shahtin (Hajian and Lotfollahi-Yaghin 2015), Hefner (Allen 1968), Marciano (Moghaddamnia et al. 2009), Stephen Stewart (McGuinness and Bordne 1972), Ivanov (Ivanov 1954), DeBruin (De Bruin 1978), Linacre (Warnaka and Pochop 1988), and Priestley Taylor (Priestley and Taylor 1972). Also, to compare the mentioned methods with the amount of evaporation from the evaporation pan, the measured evaporation information was received from the pan at the dam station. In the second section, the construction of floating concrete covers was started using the lightweight concrete construction method. Various materials were used to conduct tests and make samples, including type 2 cement, whose physical and chemical characteristics are presented in Tables 1 and 2, respectively. The water used in this research was the drinking water of Isfahan city. Coarse-grain materials used in this research were Leca 0-4, Leca 4-10, and perlite. The specific weight of Leca seeds is 330-430 $kg/m^{3,}$ and they absorb water, about 18% of their volume. According to STM-C332, the specific weight of light-grained perlite is 250-300 kg/m^3 (STM-C332 1999), and other structural properties of perlite are presented in Table 3. The production of concrete in this research is a high-strength light type, and the absolute volume method was used to calculate the proportions of the mixing plan. The specifications of the final mixing plan are given in Table 4.

Table 1: Physical characteristics of the used cement

Physical Parameters	Autoclave expansion(%)	Compressive strength (kg/cm^2)				Final setting time (min)	Initial setting time (min)	Blaine (cm^2/gr)
		2 days	3 days	7 days	28 days			
Sepahan Cement	0.08	180	250	410	550	150	210	3500
Standard deviation	0.03	15	20	25	25	30	30	100
National standard of Iran	<0.08	-	>100	>175	>315	>45	<360	>2800
European standard	-	>100	-	-	>425	>60	-	-

Table 2: Chemical characteristics of the used cement

Chemical Parameters (%)	Sepahan Cement	Standard Deviation	National Standard of Iran	European standard
SiO_2	21.10	0.50	>20.00	-
Al_2O_3	4.90	0.20	<6.00	-
Fe_2O_3	4.00	0.20	<6.00	-
CaO	64.20	0.70	-	-
MgO	2.20	0.20	<5.00	-
CL	0.025	0.005	-	<0.10
SO_3	2.20	0.20	<3.00	<3.50
L.O.I	1.00	0.30	<3.00	<5.00
I.R	0.35	0.20	<0.75	<5.00
Free CaO	1.30	0.30	-	-
Total Alcalis	0.75	0.05	-	-
C_3A	6.00	1.00	<8.00	-
Cr+6	<0.009	-	-	-

Table 3: Properties and constituents of perlite stone

Material used Specification	content percentage	Properties	Unit	Amount
Silica	72-76	Melting point	˚C	1280-1350
Aluminum oxide	10-14	Special Weight	g/cm^3	0.08-0.12
iron oxide	0.5-2	toughness	Mohs	5.5-7
Calcium oxide	0.5-2	Thermal conductivity	w/m.k	360
Potassium oxide	2-5	specific surface	m/g	1.89
Sodium oxide	2.5-5	Color	-	White
Heat loss	1-3	Shape	-	Spherical
Porosity	60	acidity	-	Neutral

Table 4: Specifications of the final mixing plans

Sample name	Weight (gr)	Volume percentage	w/c (Water/Cement)
Leca 4-10	49.98	70	0.45
Leca 2-4	63.49	75	0.45
Perlite	35.26	55	0.45

A ball mold with a diameter of 7 cm was used to prepare floating coverings. At first, the inner surface of the molds was greased with oil so that the hardened concrete could be easily separated from the mold. After preparation, cement mortar was poured into the molds to half of the volume of the mold, and after placing the fibers, the mold was filled with mortar (Figure 1). To prevent a ball filled with mortar from opening, a rubber band can be used and placed around the ball mold. After 24 hours, the samples were taken out of the mold and transferred to the ponds for processing. It should be noted that the compressive strength test for the samples was performed according to the BS 1881 regulations (Standard, B. 1986).

Figure 1- The stages of making samples

Also, to investigate the effect of placing concrete balls on the water surface of the reservoirs on the water quality of the reservoirs, the quality of water samples was tested based on EC and pH parameters. The suitable location for the project was chosen 15 kilometers northwest of Isfahan in the research lands located on the southwest side of Isfahan University of Technology, with longitude 51˚ 31´ 49″ and latitude 32˚ 42´ 24″. In this research, 12 tanks were placed in the pit, including four treatments (3 different coverings and controls), and each treatment with 3 replications was used in a completely randomized block design. According to the surface of the tanks used in this research (0.754 square meters), 140 lump concrete samples were placed on each tank. In other words, for each type of concrete, a total of 420 pieces of floating concrete were prepared. After preparation, the concrete samples were transferred to the study farm of the university to be placed on the surface of the tanks. In order to measure water level changes and record data related to evaporation losses from these tanks, rulers were embedded in their walls. After placing the floating balls on the surface of the tanks, data collection was carried out once a day for three months from August 30 to the end of November, and the amount of water level changes was measured by reading the indicators. Figure 2 shows the stages of tank preparation and placement of floating balls.Statistical analysis of this research by SAS 9.4 was done. Also, to evaluate the accuracy of different methods and to determine the best method of estimating evaporation from the reservoirs and agricultural water ponds, the parameters of RMSE[1], MBE[2],

[1] Root Mean Square Error

[2] Mean Bias Error

NRMSE[3], d[4], and R^2 [5] were used (Sullivan 2018; Willmott 1981; Liaghat et al, 2024; Ahmadpari and Khaustov, 2025):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Esi - Eoi)^2}{n}} \quad (1)$$

$$MBE = \frac{\sum_{i=1}^{n}(E\,oi - Esi)}{n} \quad (2)$$

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{n}(Esi - Eoi)^2}{n}} \times \frac{100}{\bar{E}oi} \quad (3)$$

$$d = \frac{\sum_{i=1}^{n}(Esi - Eoi)^2}{\sum_{i=1}^{n}(\,|Esi - \bar{E}si| + |Eoi - \bar{E}oi|)^2} \quad (4)$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(E\,oi - \bar{E}oi)(Esi - \bar{E}si)}{\sqrt{\sum_{i=1}^{n}(Eoi - \bar{E}oi)^2 \sum_{i=1}^{n}(Eoi - \bar{E}oi)^2}}\right] \quad (5)$$

Where Eoi and Esi are the simulated and observation evaporation values, $\bar{E}oi$ and $\bar{E}si$ are the average simulated and the average observation evaporation values, respectively, n is the number of samples.

Figure 2- Steps for preparing tanks and placing concrete covers at Isfahan University of Technology site

3. Results and Discussion

The results of the statistical parameters for the evaluation of different daily and monthly evaporation estimation methods are presented in Tables 5 and 6, respectively.

Table 5: Statistical and regression indices for estimation methods of daily evaporation from the free surface

Evaporation estimation model	RMSE	MBE	NRMSE	R^2	d	slope of the regression (b)	intercept of the regression(a)
Meyer	1.45	0.51	0.22	0.94	0.88	0.81	0.20
Penman	2.26	1.11	0.35	0.84	0.72	0.90	-12.79
Shahtin	2.91	1.45	0.45	0.79	0.63	0.29	1.03
Hefner	3.53	1.75	0.55	0.66	0.55	9.14	1.10
Marciano	3.50	1.74	0.54	0.70	0.55	0.63	18.78
Linacre	1.06	0.43	0.16	0.96	0.98	0.97	0.13

[3] Normalized Root Mean Square Error
[4] Willmott index of agreement
[5] Coefficient of determination

Table 6: Statistical and regression indices for estimation methods of monthly evaporation from the free surface

Evaporation estimation model	RMSE	MBE	NRMSE	R^2	d	slope of the regression (b)	intercept of the regression(a)
Stephen Stewart	3.91	3.22	0.72	0.67	0.52	0.14	1.11
Ivanov	0.97	-0.08	0.17	0.96	0.98	1.08	-0.62
Priestley Taylor	2.84	-1.32	0.45	0.79	0.69	0.55	2.22
DeBruin	1.11	0.18	0.20	0.96	-1.02	1.04	-0.33

As shown in Table 5, among the daily evaporation estimation methods, the Linacre method was the best method based on statistical indicators because it had the lowest RMS, MBE, and NRMSE values and the highest of d and R^2 coefficients. Therefore, this method had the most agreement with the measured data. The superiority of Linaker's method showed the effect of temperature in estimating the evaporation from the free surface of the reservoirs and agricultural water ponds. On the other hand, the comparison of monthly evaporation estimation methods based on the comparison of statistical parameters showed that the two methods of Ivanov and DeBruin were the best in estimating evaporation from the free surface of water reservoirs, with close results, and the most agreement was observed with the measurement data from the evaporation pan. Althoff et al.'s (2019) studies in the Savanna region of Brazil also indicated the better performance of Koehler et al.'s methods and Linacre's method.

The results of the compressive strength test showed that the samples made with Leca 2-4 had the highest, and the perlite samples had the lowest compressive strength (Table 7). This is because Leca aggregate is more incompressible than perlite aggregate.

Table 7: Classification of lightweight concrete based on compressive strength

Consumable lightweight	Lightweight percentage	Compressive strength of cubic sample (MPa)
Leca 4-10	75	0.056
Leca 4-10	70	0.071
Leca 4-10	65	0.078
Leca 2-4	80	0.067
Leca 2-4	75	0.08
Leca 2-4	70	0.091
Perlite	60	0.042
Perlite	55	0.050
Perlite	50	0.058

The comparison of the Leca samples shows that the Leca 2-4 concrete samples have smaller grains than the Leca 4-10 and have less void space and, as a result, higher density. Therefore, it can be stated that Leca 2-4 concrete balls have higher compressive strength. Also, the results showed that among the different ratios of water to cement in each type of concrete, concrete samples with a ratio of water to cement equal to 0.4 have higher compressive strength.

The results of the water quality tests of the reservoirs are presented in Table 8. As the results show, the use of concrete covers did not cause a significant change in the water quality of the tanks, and therefore, the use of these floating balls is qualitatively unimpeded.

In the section investigating the rate of evaporation from covered surfaces and comparing it with the control condition (without placing the covering on the free surface of water), at first, the normality test of the data was performed using the Kolmogorov-Smirnov method (Massey 1951) and the Shapiro and Wilk test (Shapiro and Wilk 1965).

Table 8: Average value of conductivity and electrical conductivity of floating coverings after the data collection period

Sample	pH	Electrical conductivity(μS/m)
Control	8.8	228
Perlite	9.5	273
Leca 2-4	8.7	267
Leca 4-10	8.9	269

The results showed that the assumption of normality of the rest of the data is acceptable at a significance level of 5% and the rest of the data are normal at the confidence level of 95%. Further, the homogeneity of variances test was performed using Levene's method (Levene 1960), and the results showed that the variance of the data was equal in the three months of September, October, and November, and the assumption of H0 was acceptable at the 95% confidence level.

Table 9 demonstrates the results of the variance analysis of the evaluation of evaporation under the floating covers of the tanks, which was carried out based on Dunnett's test (Dunnett 1955), in different months.

Table 9: Variance analysis for evaluation of evaporation under floating covers of tanks

Month	Degrees of freedom	Mean Square	Coefficient of variation (CV)	R^2
September	3	0.77*	5.75	96.40
October	3	0.05*	6.25	74.75
November	3	0.08*	10.00	88.14

* Significant difference at the 1% level

As the Table shows, there is a significant difference of 1% between each of the treatments and the control treatment, every three months. Figures 3 to 5 indicate the average amount of evaporation from the free surface of the reservoirs in the three months of September, October, and November, respectively.

As can be seen from the three mentioned figures, during the sampling period and every three months, the control treatment has shown the highest amount of evaporation. Figure 3 shows that in September, the lowest rate of evaporation was related to tanks with Leca 4-10 covering, and this covering performed better than other coverings at the beginning of the data collection period. Meanwhile, based on the results of Figures 4 and 5, in October and November, respectively, Leca 2-4 covering was the most effective covering in reducing evaporation. The reason for this change in two months is that Leca 4-10 concrete balls have a coarser grain size and water penetration into the holes; therefore, they lose more water through evaporation over time. In the comparison of other research, Alvarez et al. (2006) reported a daily evaporation reduction of 50% for aluminum covering, and for polyethylene covering with various paints reported 80%. In each of the mentioned three months, the perlite covering has been assigned the third rank in terms of its effect on reducing evaporation. Mazaheri and Abedi Koupai (2017) investigated the performance of polystyrene, aluminum-coated polystyrene, and polycarbonate floating covers in reducing evaporation from the surface of water storage pools. Using these types of covers, evaporation can be reduced by up to 86%. The results of their research showed that the polystyrene cover is more suitable for reducing evaporation from the free surface of water than the other two covers. The polystyrene cover was less expensive than the polycarbonate cover, but at the end of the period, the polycarbonate cover showed better durability than the other two covers. Moradi Mazreno et al. (2013) investigated the rate of evaporation reduction using Unilite pieces from the water surface of agricultural ponds for two months in the Aghda region of Ardakan city in Yazd province. The rate of evaporation reduction from the pan with 90% water surface coverage compared to the pan without coverage was 51.6.

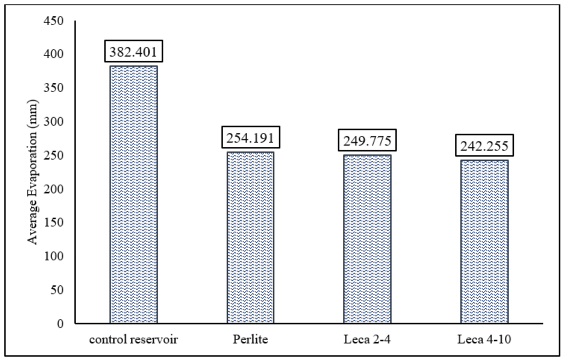

Figure 3- Average rate of evaporation from the free water surface in September

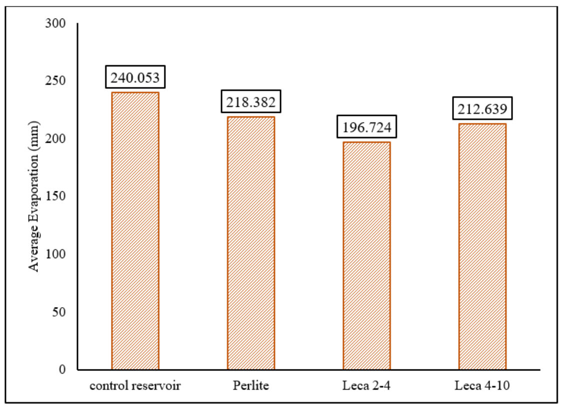

Figure 4- Average rate of evaporation from the free water surface in October

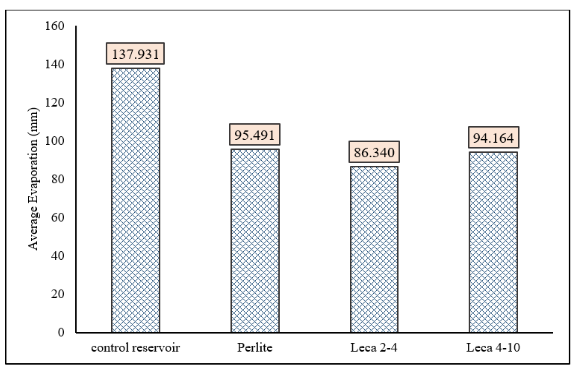

Figure 5- Average rate of evaporation from the free water surface in November

4. Conclusions

In the first section of this research, evaporation from a small recharge pond by daily and monthly evaporation estimate methods such as Meyer, Penman, Shahtin, Hefner, Marciano, Stephen Stewart, Ivanov, DeBruin, Linacre, and Priestley Taylor calculated; Also, by making concrete balls and using those floating on the surface of open water tanks, the amount of evaporation reduction from the surface was investigated. Results demonstrated that the Linacre and Ivanov and DeBruin methods were the best methods for estimating of evaporation rate as daily and monthly evaporation estimation methods, respectively.This research observed that the use of floating covers has decreased the rate of evaporation from the free surface of water tanks. The results showed that during the data collection period, the average reduction in evaporation from the surface of coated tanks was the highest for the tank containing Leca 2-4 concrete balls, and this covering, with a 42.7% reduction in evaporation, was the best. Additionally, Leca 2-4 is introduced as the most effective cover in reducing evaporation from the free surface of agricultural water ponds under the climatic conditions of the Zayandeh-Rood dam reservoir. The limitation of this study was that data collection was conducted over a period of three months. If a longer period of time, such as 12 months, were allocated for data collection instead of three months, better results could be expected.

Author Contributions:
Jahangir Abedi Koupai: Material preparation, data collection, and analysis.
Maryam Peiravi: Material preparation, data collection, and analysis.
Elham Fazel Najafabadi: writing-original draft preparation

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