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The effect of cement replacement with eggshell powder on the sorptivity index of concrete

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ABSTRACT

Most concrete structures undergo severe durability issues throughout their service of life. The transition and movement of water through concrete structures is one of the main issues in the aspect of durability. The main aim of this study is to investigate the effect of cement replacement in various ratios with eggshell powder on the sorptivity (capillarity water absorption) capacity of concrete. Eggshell is a bio-waste material obtained from bakers, restaurants, and patisseries. Disposing of this waste material in landfills results in health hazards and causes environmental pollution. The use of eggshell powder in concrete, which is the most used and essential building material after water all over the world, is a beneficial way both minimize the detrimental effects of this waste on living health and the environment and also ensure the sustainability of the materials in concrete. In this paper, five different eggshell powder substitutions as 0%, 5%, 10%, 15%, 20% were employed in experimental analyses. The sorptivity index of concretes was measured at the end of each 5, 10, 15, 30, 45, and 60 minutes. The test results indicated that the sorptivity namely capillary water absorption decreased with up to a level of 5% replacement and increased with the other replacement ratios including 10%, 15%, and 20% when compared with the control concrete's result. This is attributed to the ESP may act as a better inert filler when replaced with cement up to a level of 5% to reduce the capillary pore, increase the compactness of concrete microstructure, impermeability and restrain the transition of water in the concrete structure.

1. Introduction

Concrete is the most used and essential construction material after water all over the world (Güneyisi et al., 2014; Umar et al., 2021; Mermerdaş et al., 2021). Most concrete structures undergo a variety of durability problems within their service of life (Yücel et al., 2020; Kurtoğlu et al., 2018). One of the most important parameters of concrete in the aspect of durability is permeability. The higher impermeable microstructure means higher strength and durable concrete. It is expected to be relatively impervious of concretes when durable concrete is targeted. The impermeable property of concrete is very important for structures including dams, water storage, concrete pipes, and highways (Sümer, 1994). One of the most important factors that affect the durability of concrete is the transfer of liquids within the concrete structure. The water transferability of concrete determines its durability and strength throughout its service of life. As we know today, concrete with low water permeability shows better strength and durability properties and has a higher resistance to chemical attack. (Ramezanianpour et al., 2011). In concrete structures, the penetration and accumulation of water may cause some undesirable physical and chemical problems. These problems generally are resulted from freezing-thawing cycles of water causing disruptive pressure and cracking, harmful chemical ions (Chloride, Sulphate) diffusions into the structure of concrete by water resulting in the corrosion of reinforcing steel, high humidity by water accumulation affecting the thermal comfort, etc. If the penetration and transition of water into the concrete structure is not prevented, the concrete structure will likely be damaged and its useful life

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will be shortened (Lu et al., 2020; Hong et al., 2020; Karasin et al., 2022).

In projects where long service life is desired, the concrete void structure should be kept under control as the durability of concrete is highly related to its void structure (Türk and Demirhan, 2017). The interaction of potentially detrimental substances with concrete could be a trigger for its deterioration process. The permeability properties of concrete depend on both the void ratio and whether the spaces are interconnected or not. And, as the void ratio and the interconnection of them with each other increase, the penetration and transfer of detrimental substances and water into the concrete structure get easier. Therefore, the concrete gets damaged easier and its durability decreases (Tokyay and Erdoğdu, 2011). For the reasons mentioned above, the water permeability of concretes should be examined and it becomes more of an issue to get necessary precautions in the design phase of concrete.

Three main procedures command the water transition in cementitious structures. These are capillary absorption, diffusion, and penetration. Penetration can occur only in the condition that the material is in a fully saturated environment. Almost most materials are in a partially saturated environment, and the water transport is generally generated by diffusion and capillary absorption. Diffusion is the movement of ions because of a concentration gradient while, sorptivity occurs with the transfer and movement of water through capillary action in short-term exposure to in partially dry concrete (Castro et al., 2011). In extended words, sorptivity is the absorption of water by tiny pores in cement-based composites with surface interaction and provides a measure of permeability, microstructure, and durability. In very tiny pores, the water rise by the effect of capillarity. The low capillary water absorption means impermeable and durable concrete (Al-Goody, et al., 2015).

In the literature review, some studies have been encountered to evaluate the sorptivity of concrete mixtures. Al-Goody et al. (2015) conducted a study to investigate the effect of nano-silica and fly ash utilization on the sorptivity index of self-compacting concrete. In their study, four different self-compacted concrete were designed and in all concrete series, the nano-silica was incorporated into concrete with replacement levels of 0, 2, 4 and 6%. Firstly, self-compacted concrete mixtures were cast without fly-ash, whereas the other second, third and fourth concrete mixtures were produced at substitution levels of fly ash in 25, 50, and 75%, respectively. The sorptivity coefficients were measured for each series at the end of 28 and 90 days. They concluded that the increase in the nano-silica content resulted in a systematic decrease in the sorptivity index. However, the increase in fly ash content until the 50% replacement level decreased the sorptivity index. Bozkurt and Yazıcıoğlu (2010) performed an experimental study to look into the effect of incorporation of pozzolanic materials and curing regimes on the capillary water absorption properties of light-weight concrete. Three different concrete mixtures were designed in experimental program: one was control concrete mixture including no pozzolanic material, the last one was including 20% of fly ash (FA) and the last one is including 10% of silica fume (SF) as a replacement for the cement by weight. Both mixtures include pumice as lightweight aggregate. The specimens were cured in three different conditions: standard 20 °C water, sealed and air-cured for 28 days. The test results indicated that the silica fume introduced concrete gave lower sorptivity coefficient values regardless of curing conditions and concrete age when compared with control and concrete including fly ash. Liu et al. (2022) investigated the effect of fly ash, limestone, calcined clay, and curing age on the resistance to water penetration of seawater and sea-sand concrete. They reported that the low water to binder ratio with increasing curing age improved the water resistance. Also, they gave the information that increasing the water-resistance of concretes with fly ash, limestone and calcined clay content. Tanyıldızı (2022) performed a study to investigate the effect of cement replacement with waste ceramic powder on the capillary water absorption capacity of concrete mixtures. In this regard, cement was replaced with waste ceramic powder in proportions of 0%, 10%, 20% and 30%, and it was concluded from the study that the capillary water absorption namely permeability decreased with a replacement ratio of 10%. However, after 10% substitution rate, capillary water absorption increased with 20% and 30% substitution rates. Tosun and Şahin (2015) searched the capillary water absorption of concrete containing recycled coarse aggregate which was obtained from structural waste. In the experiment, the coarse aggregate was replaced with recycled aggregate in levels of 0%, 15%, 30%, 45%, and 60%. The capillary water absorption test was performed in the period of 1, 4, 9, 16, 25, 36, 49, and 60 minutes. They concluded that the capillary water absorption decreased with the increasing the recycled aggregate replacement level.

This study focuses on investigations of the effect of replacing cement with eggshell powder which is a bio-waste material obtained from bakeries, restaurants, poultry farms, and patisseries (Hamada et al., 2020) on the sorptivity index (capillary water absorption) of concrete. Utilization of these types of wastes in concrete as cement substitute material has been used for years and seems a beneficial way both reducing carbon dioxide emissions to the ecosystem in the production of cement and minimizing the cost of concrete. Also, the possible threat of waste to the environment and living health may be impeded by recycling way. At this juncture in this study, the cement was substituted with eggshell powder at replacement levels of 0%, 5%, 10%, 15%, and 20%. In total, 15 cubic specimens with 50 mm cubic size including the control concrete mixture were cast (three specimens for each replacement level) at constant water-to-binder ratio of 0.30. Concrete test specimens were cured in the water as fully immersed for 28 days and dried in an oven at 100±5 °C till they reached the constant mass after completing the water curing process. Then, specimens were put in sorptivity test mechanism and removed at the end of the time of 5, 10, 15, 30, 45, and 60 minutes to calculate absorbed water quantity by weighing at the accuracy of 0.01 g. The sorptivity index of each concrete specimen was determined and the test results were evaluated for each replacement level. Also, the relationship between water absorption and sorptivity for all periods was investigated by regression analysis. It was noticed that the sorptivity coefficient decreased with the 5% replacement ratio with eggshell powder and increased with the other replacement ratios compared with control concrete. Also, a strong relationship between water absorption by mass and sorptivity of concrete was revealed by regression analysis. The results showed that the usage of eggshell powder up to a level of 5% as a cement substitute can improve the impermeability of namely the durability of concrete mixtures.

2. Experimental Program

2.1. Materials

In this study, Portland cement of CEM I 42.5 R was supplied from the cement factory of Yurtçim from Muş (Yurtçim, 2021). The eggshell was obtained from the bakers, restaurants, and patisseries as bio-waste. The cleaning process of eggshells was applied before drying by an electrical oven at 120 ˚C for 24 hours to dry the surface and make grinding easier. After the cleaning and drying process, the eggshell was ground in cement particle size approx. 90 µ by grinder machine as seen in Fig. 1.

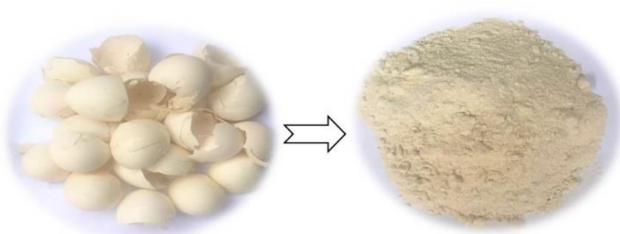

Figure 1. Eggshell powder.

The chemical and physical properties of cement and eggshell powder are presented in Table 1. The aggregate used in this study is crushed limestone with a specific gravity is 2.61 g/cm^3. The material used as a superplasticizer is polycarboxylic ether-based and named Master Glenium 128 supplied from BASF Chemistry Industry with a density of 1.061–1.101 kg/lt to obtain fluidity and decrease the cement content in the concrete mixture (Basf, 2021).

Table 1 Physical properties and chemical compositions of Portland cement and eggshell powder

Analysis Report	Cement	Eggshell Powder
SiO_2 (%)	24.18	0.59
Al_2O_3 (%)	6.57	0.15
Fe_2O_3 (%)	4,.5	0.04
CaO (%)	56.05	51.40
MgO (%)	1.33	0.54
SO_3 (%)	2.80	0.81
K_2O (%)	1.22	0.09
Na_2O (%)	0.34	0.44
Cl (%)	0.0071	0.09
Ignition Loss (%)	4.50	45.85
Specific gravity (g/cm^3)	2.95	2.77
Specific surface (cm^2/g)	4600	2950

2.2. Mixture Design

All mixtures were cast in constant binder amount with a 0.30 water to binder ratio. The cement was substituted with eggshell powder (ESP) at levels of 0%, 5%, 10%, 15%, and 20% by weight. The mold size of the sorptivity test was 50 mm cubic. Table 2 summarizes the concrete mixture ratios employed in this study. The abbreviations used for concrete mixtures containing ESP at levels of 0%, 5%, 10%, 15% and 30% are CC, E5, E10, E15 and E20.

Table 2 Mixture composition of concrete mixtures (kg/m^3)

Materials	**CC**	**E5**	**E10**	**E15**	**E20**
Cement	450	427.5	400	382.5	360
ESP	-	22.5	50	67.5	90
Water	135	135	135	135	135
Superplasticizer	4.50	4.50	4.50	4.50	4.50
0-4 mm Aggregate	836	836	836	836	836
4-8 mm Aggregate	409	409	409	409	409
8-16 mm Aggregate	534	534	534	534	534

2.2. Test Procedure

Sorptivity (Capillary water absorption)

The sorptivity is the absorption of water by way of tiny pores in cement-based composites with surface interaction and provides a measure of microstructure and durability. In very tiny pores, the water rises by the effect of capillarity. A capillary water absorption test was performed to determine the sorptivity coefficient of concrete specimens based on the standard of TS EN 13057 and ASTM C1585-04. However, some technical points such as test durations are deviated from the standards. The test was conducted on a total of 15 cubes (three specimens for each concrete mixture) with 50 mm sides after 28 days of water curing. The test specimens were dried in an oven at 100±5 ˚C till they reached the constant mass after completing the curing process. The sides of the cubes are covered with paraffin to obstruct water suction of them from the sides of the cubes. Then, specimens were removed at the end of the time of 5, 10, 15, 30, 45, and 60 minutes from the test mechanism and weighed at the accuracy of 0,01 g. The sorptivity index or coefficient of each concrete specimen was calculated following Eq. (1) and the test results were evaluated for each replacement level.

$$S = (Q/A)/\sqrt{t} \tag{1}$$

where;

S is the sorptivity $(cm/s^{1/2})$

Q is the volume of the water absorbed (cm^3)

A is the surface area in contact with water (cm^2)

t is the time (s) .

Then, the square root of the elapsed time versus Q/A was plotted and the sorptivity index (capillary water absorption coefficient) was determined from the slope of the linear relationship of the best fit line. Fig. 2 shows how to interact the surface of concrete specimens with water during the capillary water absorption test.

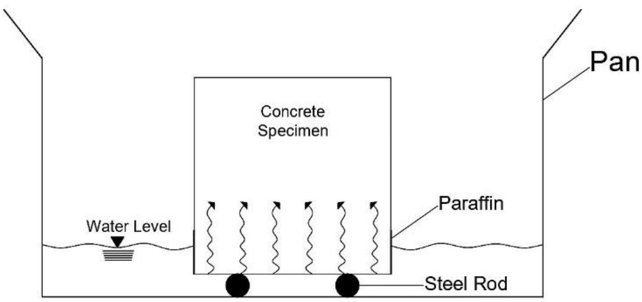

Figure 2. Detail of sorptivity test.

3. Results and Discussion

The sorptivity index was measured at a defined time for each concrete mixture at the end of the capillary water absorption test. Fig. 3 presents the sorptivity test results of the concrete mixtures at the end of the 5 minutes. The sorptivity index values vary between 2.05 and 2.71 kg/($m^2.h^{0.5}$) measured at the end of 5 min. The results indicated that the sorptivity index values decreased with incorporating 5% eggshell powder but increased by the contents of 10, 15, and 20% eggshell powder compared to control concrete mixture. Replacing cement with eggshell powder at a level of 5% decreased the sorptivity index for the 5 min-interval by about 5.5%. However, in substitution levels of 10, 15, and 20%, the sorptivity index increased about 6.45, 12.0, and 24.9% compared to control concrete respectively (as seen in Fig. 3).

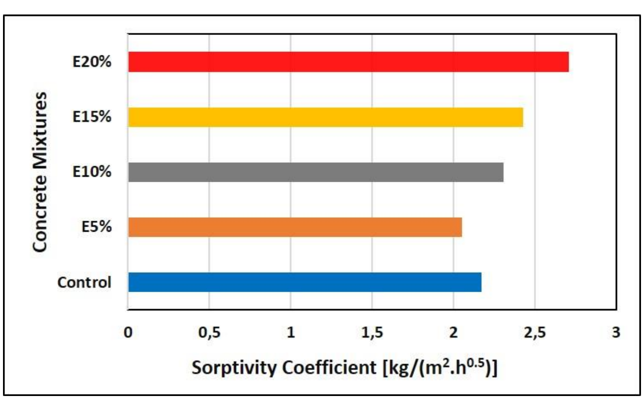

Figure 3. Sorptivity coefficients of concretes at 5 minutes.

At the end of the time of 10 min. the high and low sorptivity index value was measured as 1,52 and 2,35 kg/($m^2.h^{0.5}$) for mixtures of again E5 and E10 respectively. For the time interval of 10 min., the sorptivity index decreased by 14.6% but increased by 5.6, 18.0, and 32.0% for the E10, E15, and E20 mix. respectively as given in Fig. 4.

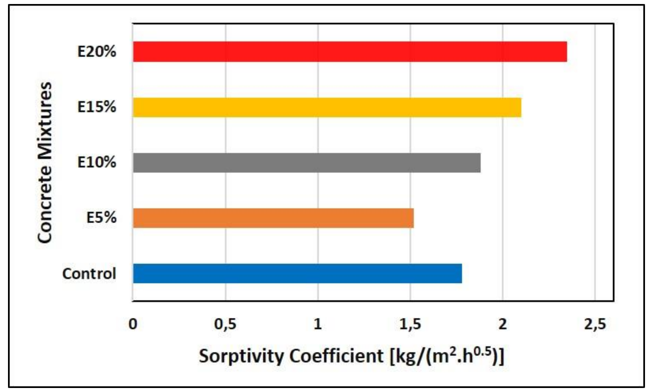

Figure 4. Sorptivity coefficients of concretes at 10 minutes.

After 15-min. water exposure interaction, the sorptivity index values were determined as 1.47, 1.23, 1.57, 1.87, and 2.02 kg/($m^2.h^{0.5}$) for CC, E5, E10, E15, and E20 respectively. The sorptivity index decreased by 16.3% for the E5 mixture, but increased by 6.8, 27.2, and 37,4% for E10, E15, and E20 mixtures respectively presented as in Fig. 5. After 30 min. water exposure, the sorptivity index values were determined as 1.04, 0.88, 1.18, 1.51 and 1.73 kg/($m^2.h^{0.5}$) for mixtures CC, E5, E10, E15 and E20 respectively. The sorptivity index decreased by 15.4% for the E5 mixture, but increased 13.5, 45.2 and 66,4% for the E10, E15, and E20 mixtures respectively respectively (as seen in Fig. 6).

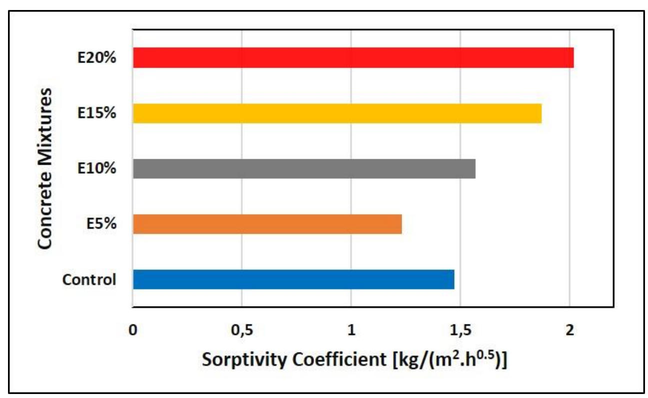

Figure 5. Sorptivity coefficients of concretes at 15 minutes.

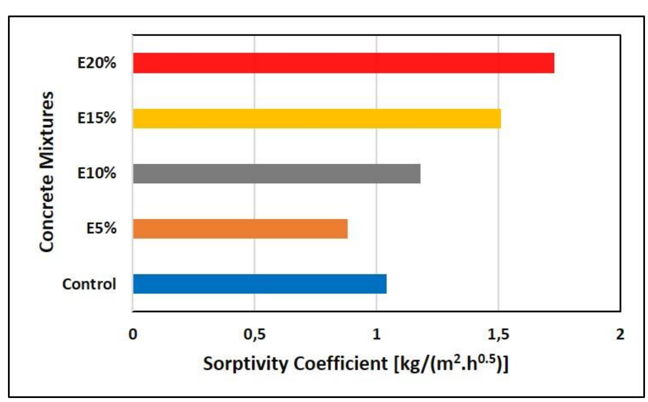

Figure 6. Sorptivity coefficients of concretes at 30 minutes.

The sorptivity index were determined as 0.93, 0.71, 1.09, 1.37 and 1.51 kg/($m^2.h^{0.5}$) at the end of 45 min. for the CC, E5, E10, E15, and E20 mixtures respectively. The sorptivity index decreased by 23.7% for the E5 mixture but increased 17.2, 47.3

and 62,4% for the E10, E15, and E20 mixtures respectively as demonstrated in Fig. 7.

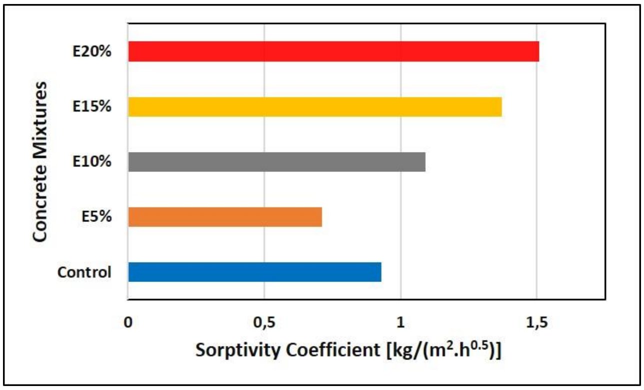

Figure 7. Sorptivity coefficients of concretes at 45 minutes.

After 60-min water exposure, the sorptivity index shaped as 0.82, 0.64, 1.01, 1.22 and 1,43 kg/($m^2.h^{0.5}$) for CC, E5, E10, E15 and E20 mixtures, respectively. For the 5% content of eggshell powder, the sorptivity decreased by 22%. The sorptivity increased at the other replacement levels by 23.2%, 48,8%, and 74,4% for E10, E15, and E20 mixtures respectively when compared with the control concrete (CC) mixture as given in Fig. 8.

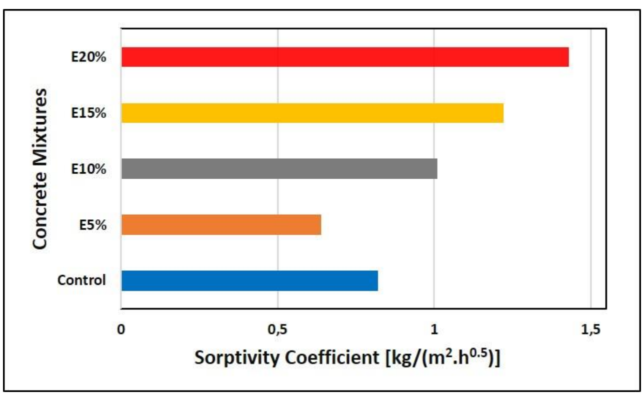

Figure 8. Sorptivity coefficients of concretes at 60 minutes.

When analyzing all sorptivity index results, it can be concluded that the replacement of cement with eggshell powder at a level of 5% increased the compactness of concrete, resulting in increased resistance against the transfer and absorption of water through the concrete microstructure. However, after a substitution ratio of 5% including 10%, 15%, and %20, it is observed that the sorptivity index enhanced, resulting in an increase in water absorption by capillary suction. All sorptivity index results for each concrete mixture are summarized in Fig. 10 for all time intervals. It is clearly seen from Fig. 10 that capillary water absorption decreases with 5% eggshell powder content but after that substitution ratio with 10%, 15% and 20%, capillary water absorption increases systematically for all time exposure.

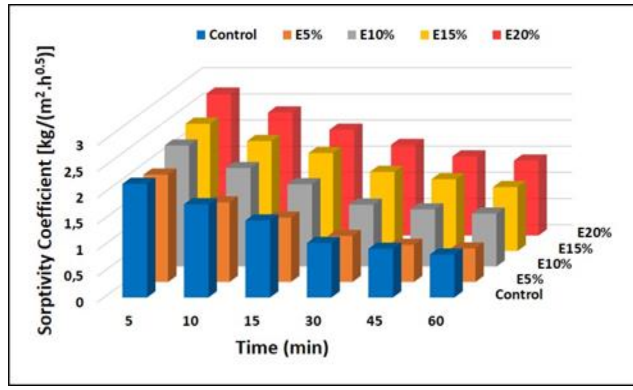

Figure 9. Summarization of Sorptivity coefficients of concretes for all time intervals.

A regression analysis was performed to correlate the water absorption by mass of concrete specimens totally immersed in water for 28 days and sorptivity index for all time intervals conducted in the study. The analyses results were presented in Fig. 10. The coefficient of determination (R^2) indicates the reliability of the relationship, which is the highest value when this reliability level is equal to 1. When all regression analyzes were examined for each time period, it was seen that there was a strong relationship between the mixture's water absorption and sorptivity index. The highest determination coefficient was measured as 0,9942 for 5 min. sorptivity test and quadratic polynomial regression equation of it was given in Eq. (2):

$$S = 0{,}0829w^2 - 1{,}7017w + 10{,}792 \quad (2)$$

where;

S= Sorptivity

W= Water absorption by mass (%) as immersed in water

The 28-days water absorption can be determined by 5 min sorptivity test with a reliability of 99,42% using this polynomial regression equation.

4. Conclusions

The sorptivity of concrete mixtures was affected by the eggshell powder content. Incorporating eggshell powder content at a level of 5% in concrete resulted in a decrease in the sorptivity index of concrete which was attributed to the improvement in compactness of the microstructure of concrete and reduction in pore sizes or volume of voids. Apart from 5%, replacement levels of 10%, 15%, and 20% were also analyzed in this study, it could be concluded that the increase in sorptivity index namely an increase in capillary water absorption capacity were observed at these replacement levels. This is likely due to occurrence of weak microstructure after the 5% replacement ratio, resulting in more water absorption and transfer of water through the microstructure of concrete. From the overall test results, it could be concluded that a 5% eggshell powder substitution rate could act as a better filler to increase the compactness and impermeability of the concrete structure, reduce the capillary void and inhibit water transfer from the concrete microstructure. Utilization of eggshell powder to improve the durability of concrete by limiting water absorption through surface interactions is a good way to minimize the harmful impact of such wastes on the and also to minimize cement production, which is responsible for the majority of greenhouse gas emissions. In further researches, it should be taken into account that other waste materials such as rusk husk ash, corncob ash, waste slate dust should be included in the process and evaluated scientifically, as well as waste eggshell powder.

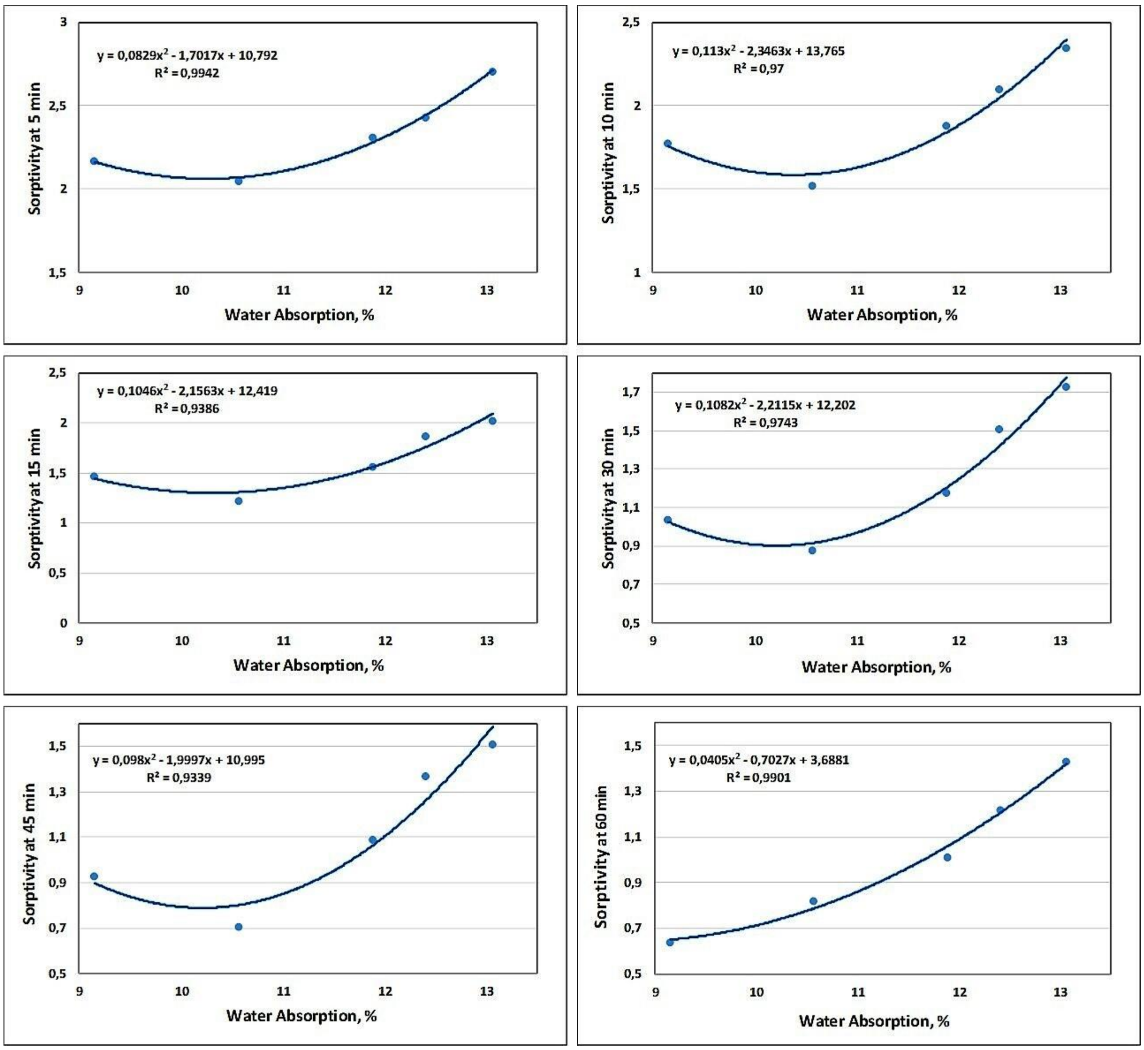

Figure 10. The relationship between water absorption by mass and sorptivity for all period

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