Properties of Pervious Concrete with Recycled Oyster Shells as Partial Aggregates Component

Nadia Razali
Section of Environmental Engineering Technology, UniKL-MICET
nadiarazali@unikl.edu.my

Nur Aini Ahmad Sani
Section of Environmental Engineering Technology, UniKL-MICET
nuraini@unikl.edu.my

Nadlene Razali
Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka
nadlene @utem.edu.my

Nurriswin Jumadi
Section of Environmental Engineering Technology, UniKL-MICET
nurriswin@s.unikl.edu.my

Abstract

This study aims to investigate the performance of oyster shells as partial aggregates replacement in a pervious concrete mixture. The experiment was carried out by replacing coarse gravel aggregates in standard concrete formulations with 10%, 20%, 30%, and 40% manually-crushed pre-treated oyster shells. For periods of 7, 14, 28, and 52 days, primary concrete properties such as pH, carbonation depth, sorptivity, compressive strength, and permeability were investigated. According to the investigations, all modified specimens outperformed control specimens, and the performance of pervious concrete was directly related to the number of replacements. Calcium carbonate was added to the mixture, which improved physical performance. However, after 28 days, the quickly achieved initial compression strengths were reduced. This research has revealed that oyster shells have much potential as an alternative material in the construction business. Furthermore, the development of pervious concrete could be an alternate environmental option for solid waste management and urban stormwater management.

Keywords: aggregates, pervious concrete, oyster shell

1.0 Introduction

Permeable paving is a term that refers to a group of surfacing treatments for roads, parking lots, and pedestrian walkways that are all aimed at allowing stormwater runoff to be absorbed. Pervious concrete, porous asphalt, paving stones, and interlocking pavers are examples of permeabilized pavement surfaces (Lu et al., 2019). Unlike standard impervious paving materials, Permeable paving technologies allow rainfall to percolate and seep through the pavement, into the aggregate layers, and into the soil beneath. Pervious concrete is a high-porosity concrete that allows water from precipitation and other sources to pass through directly, decreasing runoff and permitting groundwater recharging. Large particles are used in pervious concrete, whereas fine particles are used sparingly. The aggregates are then coated with the concrete paste, which allows water to travel through the slab. Parking lots, low-traffic zones, residential streets, pedestrian pathways, and greenhouses are examples of pervious concrete applications (Mullaney and Lucke, 2013). It is an important application for sustainable construction, and it is only one of several low-impact building approaches that builders employ to maintain water quality (Pilon et al., 2019).

Aggregate (natural or synthetic) is defined as a granular material used in concrete mixing that encompasses roughly 60% to 75% of total concrete volume (Vignesh, 2015). Aggregates should also be carefully chosen based on their shape, size, and physical qualities, as these properties will influence the material and construction process (Allen et al., 2003). Gravel, fine (e.g. natural sands), and coarse sands are the most common types of aggregates. Other materials, such as crushed shells, crushed rocks, sandstone, and reused concrete, are frequently employed for specific applications (Gibbons et al., 2003). Aggregates will improve the uniformity and durability of the final mortar and should ideally be free of silt and clay to eliminate the possibility of failure. Even though the oyster industry has impressively contributed to the development of the fisheries economy, it was also well-documented that oyster shell wastes had become an environmental concern and upcoming issue in coastal areas and landfills (Yang et al., 2010; Wang et al., 2013 and Kuo et al., 2013). These industrial by-products, consisting of 90-95% of the total oyster's weight, are perceived as no commercial value and discarded (Dridi et al., 2007). On the contrary, Chemical and microstructure analyses revealed that oyster shells are predominantly composed of calcium carbonate ($CaCO_3$) and other mineral compounds, as shown in Table 1 (Liang and Wang, 2013).

Table 1: Chemical Composition of Oyster Shell (Liang and Wang, 2013)

Compound	**Amount (%)**
$CaCO_3$	95.99
SiO_2	0.67
MgO	0.65
Al_2O_3	0.42
SrO	0.33
P_2O_5	0.20
Na_2O	0.98
SO_3	0.72

Oyster shells consist of calcite and aragonite depending on the organism's protein content (Choi and Kim, 2000). Zhong et al. (2012) enlisted beneficial physical characteristics of oyster shells as a high amount of micropores, high strength, light in mass, low density, low heat conductivity, and resistance to weathering. The simplified oyster shell physical characteristics are shown in Table 2.

Table 2: Oyster Shell Physical Characteristics (Weismantel, 1999)

Hardness (Mohs)	3.0
Specific Gravity	2.65 – 2.72
Colour	White to off-white
Particle size (µm)	0.07 -200

Many studies have been conducted on oyster shell waste as a construction material (Jegatheesan et al., 2009; Barros et al., 2009; Yang et al., 2010; Liang and Wang, 2013 and Ohimain et al., 2009). Miyaji and Okamura (2000), for example, investigated the use of crushed oyster shells and sand to improve soil stability. Lee et al. (1998) and Terada et al. (2002) used physical testing and numerical approaches to investigate the permeability and compaction properties of dredged clays and crushed oyster shells. Yoon et al. (2004) found no significant reduction in the compressive strength of mortars containing small particles of oyster shell instead of sand in trials that set out to assess the possibility of oyster shells as aggregates. The varieties of engineering design of pervious concrete/pavement are not fully explored. This study was set out to investigate the relationship between the substitution of natural calcium carbonate aggregates (oyster shell) and pervious concrete performance through physical and chemical testing

2.0 Materials and Methods

The laboratory test procedure was based on BS EN 12350-1:2019, BS EN 12350-2:2019, and BS EN 12350-6:2019.

2.1 Raw Materials

The control and modified specimens were manufactured by using locally resourced Ordinary Portland Cement (Type I), well-graded gravel (±4.5 mm), locally harvested oyster shell, and distilled water. Distilled water was used to ensure that sodium chloride (NaCl) and other mineral and impurities were removed from the water. This practice was important to provide varied control and precise outcomes in any testing. In this study, tropical oyster (*Crassostrea iredalei*) shell wastes were selected. To remove the organic and inorganic substrate from the oyster shells' surface, the oyster shells were first immersed in hot water and scraped with a clean toothbrush. The oyster shells were then air-dried for 12 hours (Adegoke and Adewuyi, 2008). After that, the oyster shells were calcined for 120 minutes at 550°C (Chiou et al., 2014). The oyster shells were then crushed by using a pestle set. Three different sieve sizes were chosen, i.e. 3.5 mm, 4.5 mm, and 5.6 mm as shown in Figure 1, and manually processed according to ASTM C136/C136M–19 (Kelley, 2009; Itaru and Yoichi, 2010).

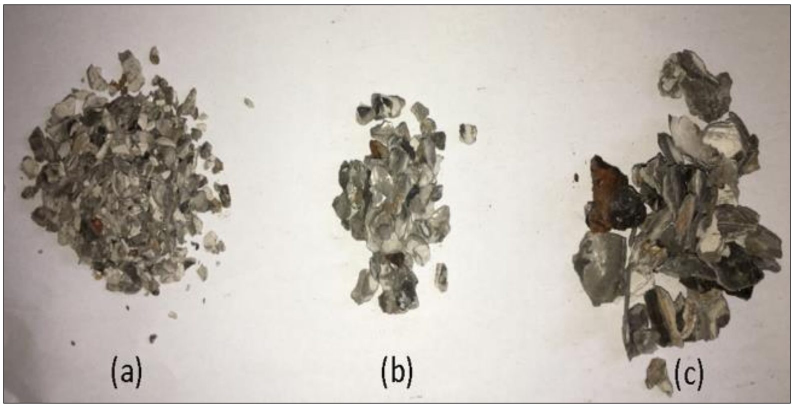

Figure 1: Oyster Shell After Sieved Process (a) 3.5 mm; (b) 4.0 mm; (c) 5.6 mm

2.2 Specimens Manufacturing

The concrete rheological properties were obtained through a slump test. A slump test was conducted to get an ideal amount of water during the mixing process to achieve normal consistency and good workability of concrete (BS EN 12350-2:2019). The raw materials were mixed by using a 1:4 ratio (1 part of cement with 4 parts for gravel) and a water to cement ratio (w/c) of 0.29 (Rogge, 2013). The result of the slump test is shown in Figure 2.

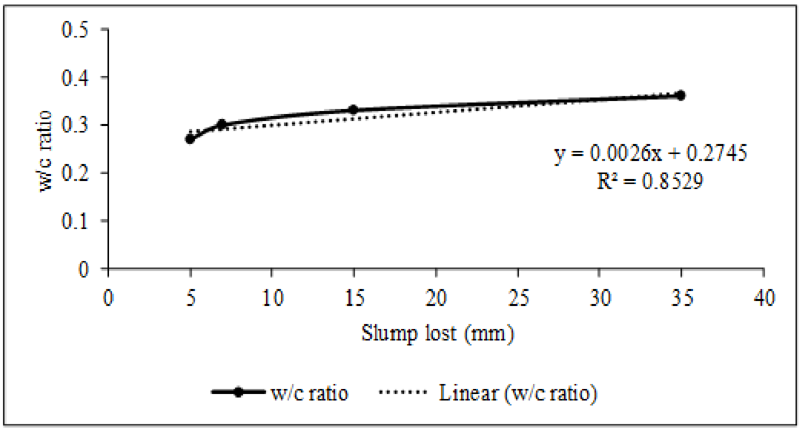

Figure 2: Slump Test Results

The standard size cubes of 40x40x40 mm were produced using a commercially available mold (Myrdal & Tong, 2018). Oyster shells were directly substituted for natural coarse aggregate at 10%, 20%, 30%, and 40% (styled as R10, R20, R30, and R40, respectively) by mass for modified mixing. The slump test equation was utilized as a starting point for developing improved formulations. The mixed mixture of control pervious concrete and oyster shell pervious concrete (based on one sample cube) is shown in Table 3 below. The specimen was demolded for 24 hours before being placed in water to cure. The 7th, 14th, 28th, and 52nd days are determined to be testing days.

Table 3: Basic Mixing Formulation

Materials	**Sample (g)**				
	Control	**R10**	**R20**	**R30**	**R40**
Cement	20.5	20.5	20.5	20.5	20.5
Coarse Aggregate	82.02	0	0	0	0
Oyster	0	8.20	16.4	24.6	32.8
Crushed Stone	82.02	73.8	65.6	57.4	49.2

2.3 Chemical and Physical Testing

2.3.1 pH

The pH value was used to determine the hydrogen ion concentration changes during the hydration process. The hydrogen ion concentration fluctuations during the hydration process were calculated using the pH value. The pH of the concrete was measured using pH strips and a pH meter (Mettler Toledo). The pH strips were dipped into the slurry for fresh concrete. The Rasanen and Penttala (2004) approach was utilized for hardened concrete (7 days and above). To eliminate measurement mistakes caused by carbonation and moisture content gradient, the concrete specimens were manually cut at a distance of 20 mm from the surface. After that, the specimen was ground into a powder. The 15g of specimen powder was mixed with 15g of distilled water.

2.3.2 Carbonation Depth

The depth of carbonation was investigated upon each mortar sample at designated testing days. The samples were sprayed with phenolphthalein, and the resulting stained material was recorded. The carbonation depth was measured by a digital caliper (to the nearest 0.01 mm).

2.3.3 Compressive Strength

The specimens were tested for compressive strength following BS EN 12350-1:2019 by using INSTRON Floor Mounted Material Testing System. Graphs were plotted showing force applied against the distance that the arm applying the pressure has moved. The data produced illustrates the stress forces in the specimens up to failure.

2.3.4 Sorptivity Test (capillary absorption)

A sorptivity test was conducted for this study by adopting the direct gravimetric method (Razali, 2014). Before this, the specimens were oven-dried for 1 hour before the sorptivity test. Then, they were placed into 5mm of distilled water in a container on glass rod support, as shown in Figure 3.

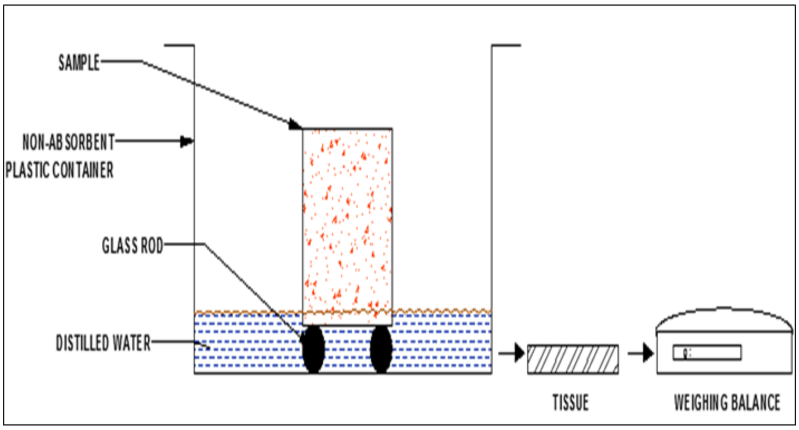

Figure 3: Sorptivity Test

The specimens were then weighed to determine the changes in weight over a specified time frame of 1, 3, 5, 10, 15, 30 minutes. A minimum of 5 measured weight gain points was then plotted onto a graph with the water absorption measured in g/m2 against the square root of time t1/2. The sorptivity was then determined from the gradient of the slope. From that, the sorptivity was calculated by using the following formula (Dias, 2000);

$$k = \frac{W}{A}\sqrt{t} \tag{1}$$

Where,

W = water absorbed (g)
A = surface area (mm^2)
k = sorptivity coefficient
t = time (s)

2.3.5 Permeability

Pervious concrete may allow water to drain freely, and it has high porosity that can be achieved by a small amount of large aggregate (Marks, 2008). Therefore, this test was conducted to examine the water flow through the void content,t illustrated in Figure 4.

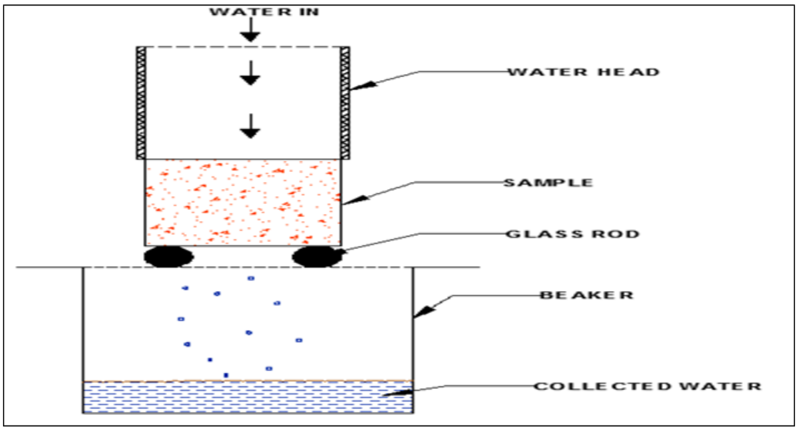

Figure 4: Permeability Test

This condition is desirable for controlling urban surface runoff to avoid the flood. Elawady et al. (2014) establish permeability equation (Equation 2) of pervious concrete is determined using the falling head permeability test and is estimated based on Darcy's Law formula, which is:

$$K = \frac{QH}{ATP} \qquad (2)$$

Where,
Q = permeated water (cm^3)
H = height of the specimen (cm)
A = surface area of the specimen (cm^2)
T = test time (s)
P = water head (cm)

Permeability is calculated by measuring its internal states like flux and pressure. In this study, water pressure was kept constant.

3.0 Finding and Analysis

3.1 pH

Figure 5 shows no significant difference in pH between modified pervious concrete with normal pervious concrete but a strong trend can be established. The fresh oyster shell has a pH approaching pH 14. However, once the carbonation reaction took place, the pH reading becoming neutral. Carbonation progressively lowers the pH in a mortar by maximizing the amount of Ca^{2+} ions. The pH variations could be attributed to differences in materials characteristics and their properties, corresponding to the extent of carbonation of the concrete.

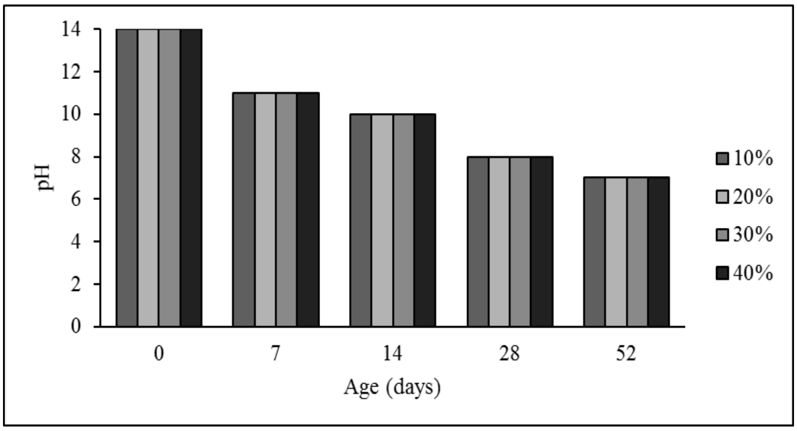

Figure 5: pH of Pervious Concrete

3.2 Carbonation Depth

Physical observations of carbonation rate throughout the testing period are shown in Figure 6. It was apparent that all formulations had carbonated throughout the study. Based on the plotted carbonation rate data shown in Figure 7, it was observed that the carbonation depth of R20 specimens was lower rather than control. However, it continuously increased from 14 days onwards. Also, R30 showed a sharp carbonation depth increase with time and had the highest carbonation depth of 9.1 mm at 52 days. This observation is consistent with the carbonation principles that carbonation depth increases with time.

Figure 6: Carbonation rate physical observation

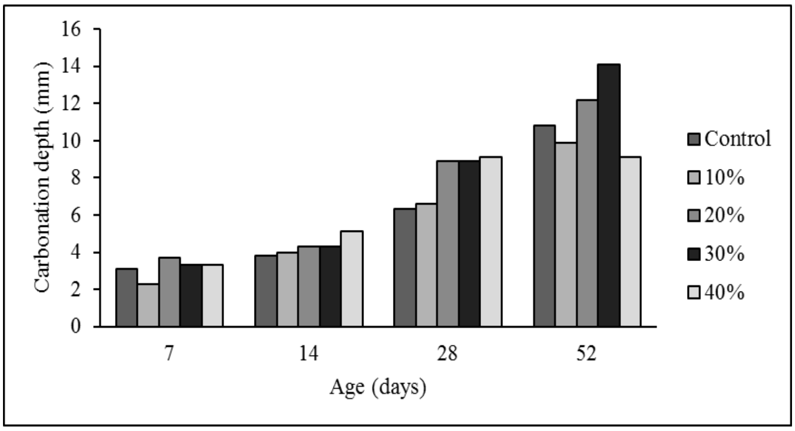

Figure 7: Carbonation Depth

During the carbonation process, the CO_2 in the surrounding environment is enough to make calcium hydroxide ($Ca(OH)_2$) reacted. This reaction can be explained through Equation 3;

$$Ca[(OH)]_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (3)$$

Type of cement, humidity, temperature, and concentration of CO_2 are several factors affecting the carbonation depth and rate. This study observed that the rate of carbonation also depends on the replacement percentage, porosity, and moisture content of the concrete. Due to high porosity, especially in R40, the amount of water in the void from curing was increased. The high amount of water can prevent CO_2 diffusion in concrete through void content. Therefore, the rate of carbonation of R40 had been hindered comparing to other formulations.

3.3 Compressive strength

As illustrated in Figure 8 below, the first 28 days showed that all modified formulations had higher strength than control, in which the higher the replacement, the higher strength would be. The strength was then becoming stagnant until the end of the testing day. It can be observed the strong similarity between Control and R10 due to non-significant replacement volume and matrix arrangement. Nevertheless, R40 conveyed an anomaly observation. R40 gained the highest strength on day 7 to lose 50% of the strength on day 14 onwards.

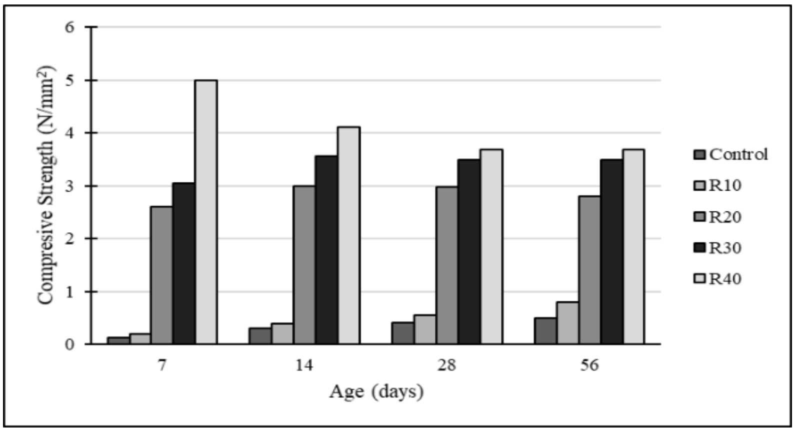

Figure 8: Compressive Strength

According to Abdullahi (2012), the compressive strength of normal concrete will increase with curing time. The strength is influenced by factors such as void ratio, unit weight, water-cement ratio, additional cementing material, aggregate size, and aggregate-cement ratio. Pervious concrete has lower compressive and flexural strengths compared to conventional concrete. This situation is because of the high porosity value due to the absence of sand (filling in the gap). Typically, the average compressive strength of conventional general concrete is approximately 21 - 28 N/mm^2 but for pervious concrete is only from 5.5 - 20 N/mm^2 (Kosmatka et al., 2002). Therefore, the interactions between aggregates and cement (binder) are important elements in the modification.

It is believed that the early strength was formed from the dilution of CaO from the oyster shell. However, with higher replacement, excessive content of CaO will reduce the moisture content of pervious concrete and makes the hydration process slower (Damone, 2010). Therefore, it might increase the porosity of pervious concrete. Hence, reducing the compressive strength of the pervious concrete (Nguyen et al., 2013). In addition, the presence of oyster shell aggregates might interrupt the granular arrangement of gravel that leads to loss of strength. This observation is supported by Yang et al., (2010), in which the effect of substitution ratio (SR) of oyster shells on the compressive strength on the 28th day was not detrimental. When the substitution of greater amounts was undertaken, the strength decreased over time long term.

3.4 Soptivity Test

Figure 9 shows the sorptivity value for various replacement rates throughout the testing period. R30 and R40 showed similar changes from day 28 onwards. It is because a high percentage of oyster shells need more water hydration process. The coarse aggregates were kept to a narrow gradation to increase void contain in pervious concrete. These results confirm the association between strength and porosity (sorptivity) in which high porosity will reduce the compressive strength of pervious concrete, as suggested earlier.

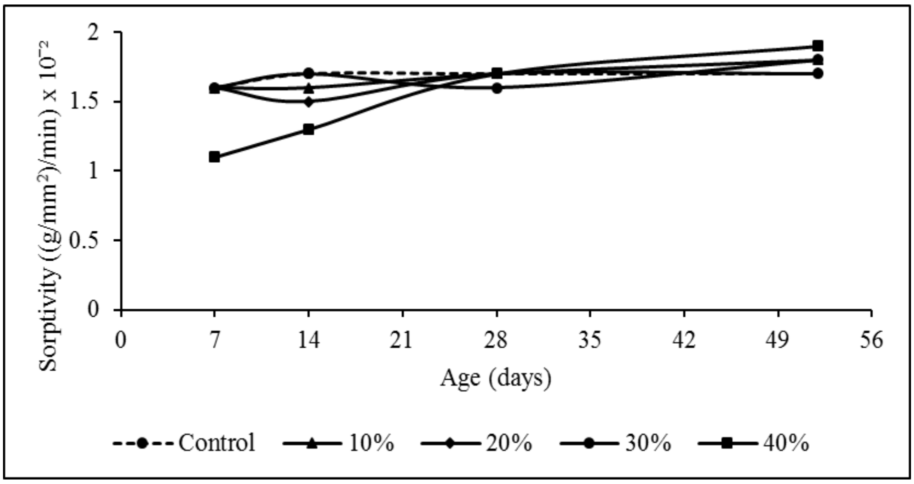

Figure 9: Sorptivity of The Pervious Concrete

3.5 Permeability

The results shown in Figure 10 proved that the performance of the pervious concrete strongly depends on the replacement rate. Overall, the permeability of the formulation showed an anomalies trend with permeability increase with lesser replacement. It can be observed that Control and R10 have similar effects. It also noted in higher replacement (R30 and R40). With fewer aggregates replacement, voids are interconnected due to their larger number of gravels, and a continuous link is formed, making the concrete permeable.

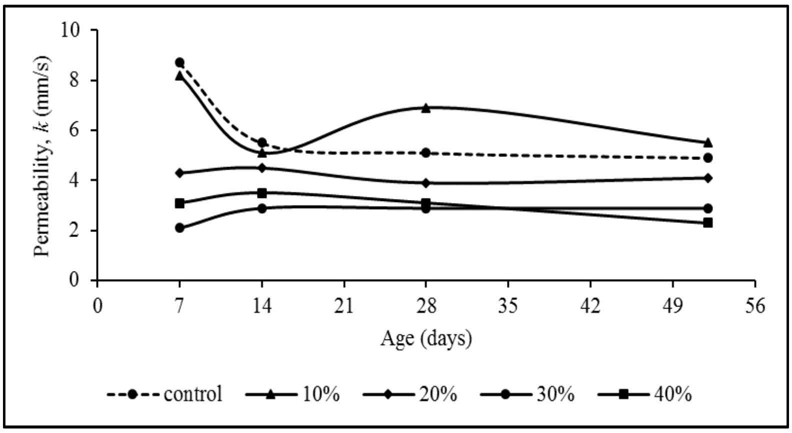

Figure 10: Permeability of The Pervious Concrete

The coarse aggregate is kept to a narrow gradation, as stated by Mrakovčić et al. (2014), to increase the void contained in previous concrete. During selection, consideration must be given to factors such as absorption and surface moisture of aggregates. This is because the aggregate's inner structure consists of solid material and voids that may or may not contain water. Therefore, it is necessary to customize the amount of water in the mixture to include the moisture conditions of the aggregate.

4.0 Conclusion

According to the testing results, the modified pervious concrete with percentages of replacement outperformed the control. These findings are consistent with each test in which the replacement rate greatly influences the performance of previous concrete. A higher replacement percentage improves the rate of pH, carbonation, and compressive strength acceleration. If the specifier is looking for an increase in sorptivity and permeability, no changes are required.

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