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Jurnal Pensil Pendidikan Teknik Sipil

Journal homepage: http://journal.unj.ac.id/unj/index.php/jpensil/index

FLY ASH AND SILICA FUME SUBSTITUTION ON COMPRESSIVE STRENGTH AND PERMEABILITY OF CONCRETE IN THE MARINE ENVIRONMENT

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P-ISSN: 2301-8437
E-ISSN: 2623-1085

ARTICLE HISTORY

Accepted:
12 April 2023
Revision:
15 September 2023
Published:
29 September 2023

ARTICLE DOI:
10.21009/jpensil.v12i3.34971

Abstract

Cement, as a concrete-forming material, is a contributor to CO2 emissions in the world. Reducing cement and substituting fly ash and silica fume as concrete substitution materials in the manufacture of concrete makes green concrete without lowering the quality of the concrete. Concrete in the marine environment is frequently destroyed by severe environmental elements, such as seawater penetration; hence, high-performance concrete materials are required. This research aims to analyze the effect of adding fly ash and silica fume on concrete compressive strength and permeability. The specimens made were then immersed in freshwater and seawater. Analysis of the compressive strength test result shows that the compressive strength values for the samples treated with freshwater or seawater have exceeded the expected compressive strength of 30 MPa. The permeability test on the test object resulted in the supplementary fly ash to the concrete immersed in freshwater having a good value, i.e., the water penetration was below that required by DIN-1045, namely 5 cm. The penetration of concrete with fly ash impressed in seawater is good only in concrete with a 10% fly ash variation. The water penetration value still meets the requirements in concrete with silica fume for all variations with freshwater and seawater treatment.

Keywords: Silica Fume, Fly Ash, Permeability, Compressice Strength

Introduction

Concrete is one of the main components of construction, both for land and sea environments. Standards that apply to concrete materials used in marine environments must have a higher compressive strength value than buildings on land (Adi et al., 2020). Research on the effect of seawater on the concrete compressive strength shows that if the concrete is soaked continuously for 28 days, it will reduce the compressive strength value. In this study, the concrete submerged in seawater at seven days of age reached a compressive strength value of 20 MPa and then decreased to 14 MPa at 28 (Wedhanto, 2017).

Buildings in a marine environment of concrete must have more specific characteristics, including high concrete quality and low permeability (Lee & Chisholm, 2005; Mohammed et al., 2003). The minimum requirement based on SNI 03-2914-1992 and DIN 1045-2 for seawater penetration is 50 mm for medium-aggressive water tightness and 40 mm for strong-aggressive water tightness. Since seawater contains chloride and sulfate chemicals that are corrosive to concrete and reinforcement, these structures require building materials impervious to seawater, slowing or extending the rate of chloride penetration into the concrete (Du Preez & Alexander, 2004; Idrees et al., 2022; Riski et al., 2015).

Innovations in concrete technology are always required to answer the challenges of concrete needs. The resulting concrete is expected to have good quality, strength, and durability in corrosive and aggressive environments without neglecting economic value (Mackechnie & Scott, 2012). To overcome this, substituting added materials as a partial replacement for concrete is one of the steps to getting quality concrete resistant to aggressive environments (Joel, 2020). The use of concrete in construction is closely related to cement production as one of the elements in making concrete (Sudarsono et al., 2022). Production of Portland cement during the manufacture of cement clinker will result in considerable CO2 emissions (Mehta, 2002; Ramezanianpour, 2014).

Reducing the amount of cement by adding or completely replacing cement is also expected to reduce production, which impacts reducing carbon dioxide exhaust emissions and global warming (Davidovits, 2008; Hannanee Ahmad Zaidi et al., 2019). Green Concrete enhances three factors of sustainability: environmental, economic, and social impact (Concrete Centre, 2007). The critical factors in identifying green concrete are the amount of Portland cement substitute, manufacturing process and method, performance, and sustainability impact (Suhendro, 2014).

Reducing the amount of cement by adding or completely replacing cement is also expected to reduce production, which impacts reducing carbon dioxide exhaust emissions and global warming. (Poon, 1999) Concrete with fly ash and silica fume is known as green concrete. However, fly ash and silica fumes have the potential to pollute the air and affect public health. Research on the effect of using fly ash and silica fume on concrete has been widely conducted by researchers in this field (Gražulytė et al., 2020; Megahed et al., 2019; Salain et al., 2020).

Research Methodology

The test object was made by adding several variations of fly ash and silica fume substitution to the concrete. The fly ash used is type F, a waste from PLTU Suralaya. The cement used is type II cement (Irawan, 2013). The test object is then immersed in different types of water, namely freshwater, and seawater, to determine the effect of seawater on concrete (Shahrabadi et al., 2017). The results of the compressive strength and permeability tests on specimens immersed in freshwater and seawater were then compared. The seawater used comes from Rancabuaya Beach, Garut Regency, West Java, which has not been affected by pollutants.

Compressive Strength Test

The compressive strength value of concrete (fc') is obtained through standard testing procedures, using a testing machine by applying a multilevel compressive load to the concrete cylinder test object until it cracks/crumbles. The SNI 1974-2011 and ASTM C39-99 are the standards of the compressive strength test. The test object is a concrete cylinder with a diameter of 15 cm and a height of 30 cm, which is pressed by a P load until it collapses. Concrete compressive strength tests were performed on specimens aged 28 days, 56 days, and 90 days. The specimens studied have been immersed in both freshwater and seawater.

Permeability of Concrete

Permeability testing utilized indirect permeability testing equipment and 15x15x20 cm cube test items following DIN 1045-2 requirements (Basuki, 2015). Tests were carried out to obtain the value of water penetration into the concrete and the permeability coefficient of concrete (Skutnik et al., 2020).

Research Results and Discussion

Aggregate Test Results

This study's fine aggregate sieve analysis test aims to determine the gradation distribution of the fine aggregate used and whether it is under the limits.

Figure 1 shows the results of fine aggregate testing of sand originating from Mount Galungung. Gradation of sand that passes sieve No.8 to No.200. The fine aggregate must meet the boundary requirements according to SNI 03-2834-2000 and can be categorized as medium sand. The specific gravity test results show that Galunggung sand has an oven-dry particular gravity of 2.16 gr, an apparent specific gravity of 2.47 gr, an average SSD weight of 2.28 gr, and a percentage of water absorption of 5.73%, and Galunggung sand used in this study has an average value fineness modulus of 2.48%.

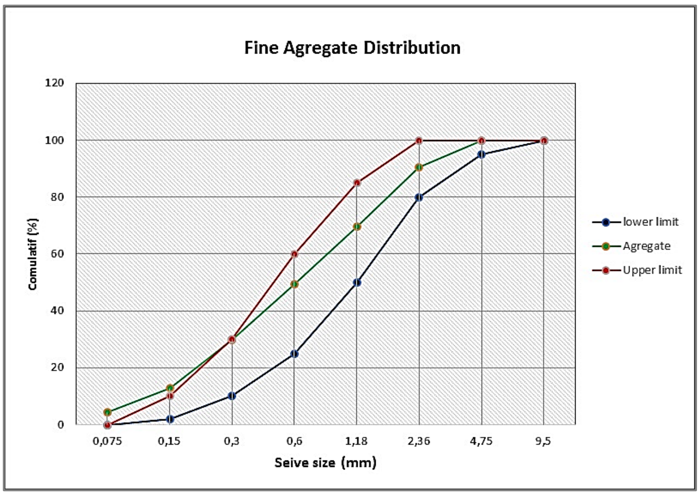

Figure 1. Fine aggregate live test results

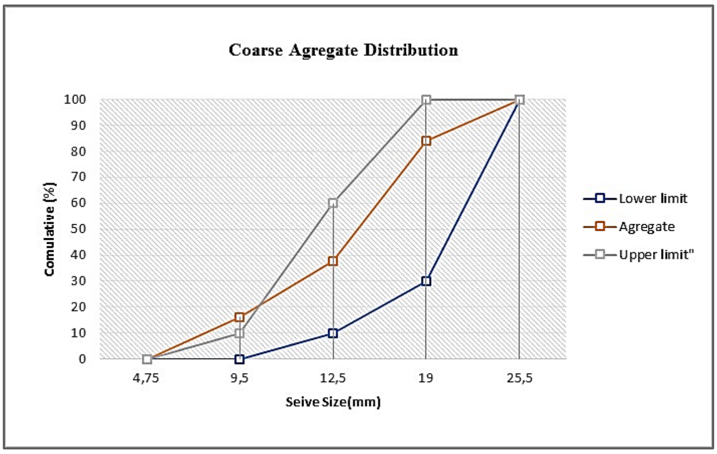

Figure 2. Coarse aggregate live test results

Gradation of sand that passes a sieve size of 4.75 mm to 19 mm. Since the pan had been well cleaned before the sieve test on coarse aggregate, there was no silt or fine residue left on the pan after the test. Based on the data from the sieve analysis of the coarse aggregate, it can be categorized according to ASTM – C33; the coarse aggregate sample from the Banjaran quarry is included in the combined gradation. The results of the coarse aggregate's specific gravity and water absorption test concluded that the average oven-dry specific gravity test was 2.68 grams, the apparent specific gravity was 2.77 grams, the SSD average weight was 2.71 grams, and the percentage of absorption water was 1.31%. While the solid content weight has an average value of 1.582 kg/liter or 1582 kg/m3, the loose content weight is 1.404 kg.

Water Salinity

The seawater used to cure concrete is pure and unpolluted, coming from Rancabuaya Beach in the Garut Regency of West Java. The results of the salt content test revealed that water had a 6.83% salt content.

Table 1. Salinity of seawater

Parameter	Method	Units	Results
Water Salinity of Rancabuaya Coast	Alpha 23 2520- Salinity 2017	%	6,83

Concrete Mix

The manufacture of concrete specimens is based on the results of ordinary concrete mixtures in which substitution materials are substituted by reducing Portland cement. Variations in adding fly ash or silica fume as a substitution material are based on previous studies by other researchers (Niveditha & Koniki, 2020). The following is the composition of the substitution material on the test object. The substitution variation of fly ash in concrete is 10%, 20%, and 30% by weight of cement, while the substitution of silica fume is 5%, 7%, and 10% by weight of cement.

Table 2. Concrete mixture of fly ash

Materials (kg/m³)	**FA10%**	**FA20%**	**FA30%**
water	205.00	205.00	205.00
OPC type II	384.38	341.67	298.96
Fly Ash	42.71	85.42	128.13
Fine Aggregate	645.32	639.13	632.22
Coarse Aggregate	1028.30	1028.30	1028.30

Table 3. Concrete mixture of silica fume

Materials (kg/m³)	**SF5 %**	**SF7 %**	**SF10 %**
Water	205.00	205.00	205.00
OPC type II	405.73	397.19	384.38
Silica Fume	21.53	29.9	42.71

Materials (kg/m³)	SF5 %	SF7 %	SF10 %
Fine Aggregate	652.19	652.19	652.19
Coarse Aggregate	1028.30	1028.30	1028.30

Figure 3. Compressive test

Fly Ash Concrete Compressive Test Result

Compressive strength testing is the primary and most important thing in determining the quality of concrete and the strength achieved. Ordinary Portland concrete (OPC) compressive strength using cement type II. Compressive strength testing is recommended until the age of the concrete reaches 90 days because it is predicted that it will only get the desired compressive strength at that time. The specimens were tested at the concrete age, reaching 28, 56, and 90 days.

It is anticipated that adding fly ash will enable concrete to use less cement while keeping the desired compressive strength. Adding variations of fly ash into the concrete of 10%, 20%, and 30% impacts the compressive strength of this concrete (Kosior-Kazberuk & Lelusz, 2007).

The following is the average compressive strength of concrete with variations in the fly ash mixture from the test results.

Table 4. Fly ash concrete compressive strength

No	Specimen codes	Average compressive strength (*fc'*) (MPa)		
		days		
		28	56	90
1	COC 0%	38.05	50.05	55,22
2	COS 0%	34,42	49.97	54,76
3	CFC10%	43,37	48,77	49,34
4	CFS 10%	37.01	43,67	45.30
5	CFC 20%	36.65	50.08	55.02
6	CFS 20%	37,73	45,69	50.88
7	CFC 30%	34,28	46,56	49,24
8	CFS 30%	34,27	43,81	46,60

The specimen code shows variations in fly ash substitution and how to treat the test object. COC is ordinary concrete treated with freshwater, while COS is ordinary concrete treated with seawater. CFC denotes fly ash substituted concrete with freshwater treatment, and CFS is fly ash concrete with seawater treatment. The percentage shows the variation of fly ash substitution in concrete.

The ordinary concrete design compressive strength is achieved at 28 days of concrete, equal to 38.05 MPa. This value has exceeded the planned compressive strength (*fc'*) of 30 MPa and the average target compressive strength (*fcr'*) of 33.9 MPa. Over time, ordinary concrete's average compressive strength value increases to 55.22 MPa at 90 days concrete.

The compressive strength of ordinary concrete increases with the age of the concrete, whether immersed in freshwater or seawater. The compressive strength of ordinary concrete immersed in seawater is lower than that of concrete immersed in freshwater (Emmanuel et al., 2012).

The results of concrete testing appear to conform with the results of other studies where adding fly ash with composition variations of up to 30% by weight of cement will increase the compressive strength of concrete (Joel, 2020).

Other studies have used fly ash up to 50% of the weight of cement in ordinary concrete. The result is that the optimum substitution value for fly ash is at 30% fly ash substitution variation (Manohar & Polu Raju, 2017; Nath & Sarker, 2011).

Furthermore, in COS0% ordinary concrete treated with seawater immersion, at 28 days, the average compressive strength reached 34.42 MPa. This matter slightly affects the decrease in compressive strength, although not too significant. The compressive strength still meets the design compressive strength and the required average (target) compressive strength. The compressive strength of concrete increased linearly up to 54.76 MPa at 56 days and 90 days of concrete. This value has no significant difference with freshwater-treated concrete.

The best compressive strength value achieved by fly ash concrete with freshwater treatment was with a variation of 20% fly ash mixture, namely COC20%, which reached a compressive strength of 55.02 MPa at 90 days of age.

In fly ash concrete immersed in seawater, the compressive strength value of fly ash concrete reached the highest compressive strength value in 20% (COS 20%) of fly ash concrete, where the compressive strength achieved was 50.88 MPa. This matter also shows that seawater reduces the compressive strength of this fly ash concrete. The optimal mixture variation in this study was a variation of 20% fly ash concrete. Giving fly ash as much as 10% and 30% compressive strength results are still below the concrete with 20% fly ash.

Silica Fume Concrete Compressive Test Result

Silica Fume Concrete has reached the design compressive strength at 28 days of concrete. At 28 days, all concrete with substitution variations of 5%, 7%, and 10% reached the targeted average compressive strength value (fcr').

Table 5. Silica fume concrete compressive strength

No	**Specimen codes**	**Average compressive strength (*fc'*)**		
		days		
		28	**56**	**90**
1	COC 0%	38.05	50.05	55.22
2	COS 0%	37.38	49.97	54.76
3	CSC 5%	46.70	46.77	49.40
4	CSS 5%	40.71	46.67	47.71
5	CSC 7%	42.93	48,26	51.60
6	CSS 7%	35.76	42.56	44.55
7	CSC 10%	39.59	44,11	47.89
8	CSS 10%	38.13	42.65	48.31

CSC denotes Silica Fume substitution concrete with freshwater treatment, and CSS is silica fume concrete with seawater treatment.

Concrete soaked in freshwater with 7% silica fume substitution (CSC7%) has the best average compressive strength value of silica fume concrete at the age of 90 days, while 10% silica fume concrete (CSS10%) has the highest compressive strength value of silica fume concrete submerged in seawater. The strength test results on the silica fume concrete test specimens show a tendency to decrease compressive strength achievement compared to ordinary concrete at 90 days. However, this value still has a compressive strength value above the targeted average compressive strength (*fcr'*), namely 33.9 MPa.

The addition of silica fume has a good effect on increasing the compressive strength at optimal substitution (Amudhavalli and Mathew, 2012; Barbhuiya and Qureshi, 2016; Srivastava et al., 2014; Tarru, 2018)

Abed et al. (2018) use up to 35% of silica fume. Their research results show that the optimum value of silica fume in ordinary concrete soaked in freshwater is at a variation of 25%.

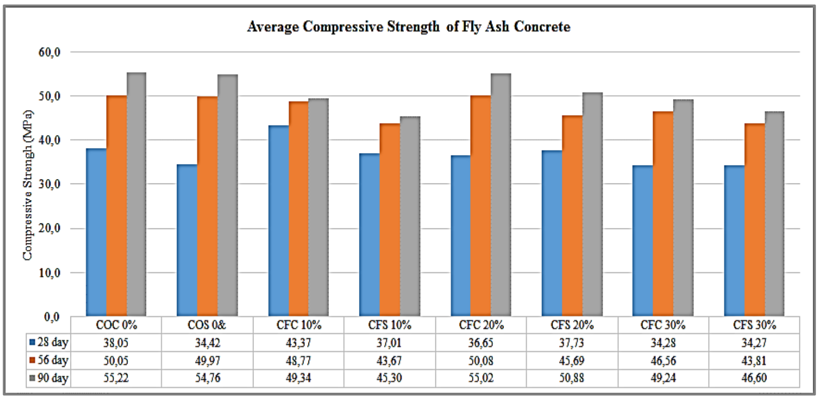

Figure 4. Average compressive strength of fly ash concrete

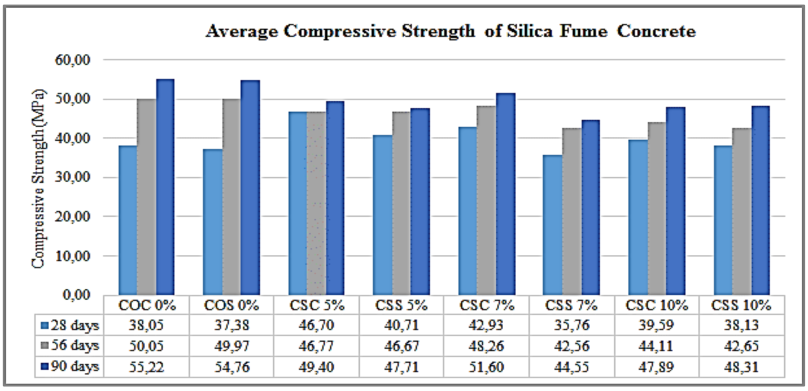

Figure 5. Average compressive strength of silica fume concrete

Permeability Test Result

Concrete permeability testing is carried out to measure how much water can travel through the concrete. The test object's dimensions are 20x20x12 cm after being submerged in liquid for three consecutive days. The test object is then highlighted so that its water absorption may be monitored afterward. The standard requirements for the permeability of concrete are based on DIN 1045; namely, the penetration or absorption of water should not exceed 5 cm.

Ordinary concrete permeability has a good value. The permeability test results showed that with a pressure of 5 kg/cm^2 for three days, the seepage rate reached 2.3 cm with freshwater treatment and 2.7 cm with seawater immersion.

Testing the permeability of fly ash concrete with freshwater immersion tends to have a good penetration value. All test results for 10%, 20%, and 30% fly ash variations are below the maximum limit.

The results of the fly ash concrete permeability test have varying values. Penetration of fluids into the concrete shows that with a pressure of 5 kg/cm2 for three days, the most significant seepage rate is in fly ash concrete; seawater attenuation reaches 10 cm for a 20% variation of the mixture. For 30% variations, the average water penetration reaches 7.3 cm, then concrete with 30 % fly ash penetration of the fluid reaches an average penetration thickness of 7 cm. This value is above the maximum threshold required by DIN 1045.

The permeability of silica fume concrete has various values. According to the results of the permeability test, the seawater attenuation of silica fume concrete had the highest average water penetration rate with a pressure of 5 kg/cm2 for three days, reaching 4.5 cm for the 7% mixture variation, 3.3 cm for the 5% variation, and an average thickness of 2.7 cm for the 10% silica fume variation.

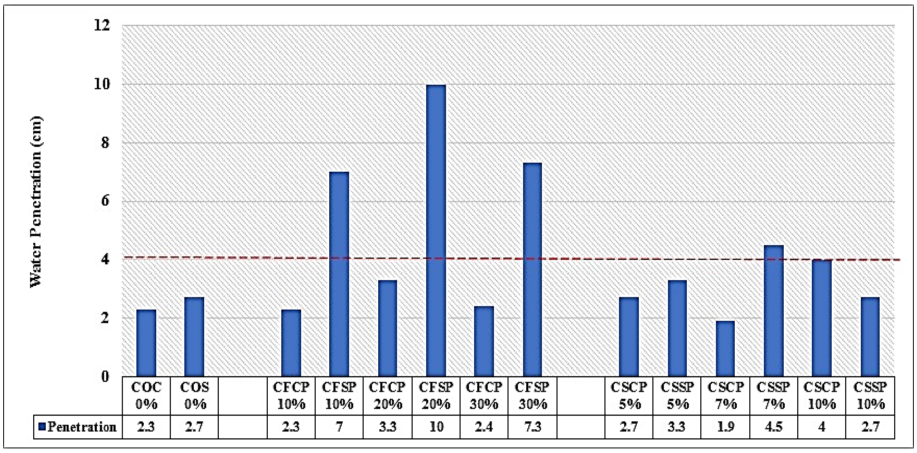

Figure 6. Water penetration in concrete after three days

From the permeability testing of all specimens with material substitution in concrete, a reasonably good concrete mixture was made by substituting silica fume in concrete. Water penetration on the test object has a fluid penetration thickness below 5 cm. The test object's value is still below the limit even after being treated with freshwater immersion and fly ash replacement. Still, the penetration value surpasses the necessary limit when the test object is treated with seawater.

Saker et al. (2008) also performed a similar test on concrete with fly ash and silica fume substitution treated with freshwater. This study yielded equivalent results, demonstrating that penetration in concrete has results below the upper limit and that silica fume concrete had lower or more waterproof penetration than fly ash replacement concrete. Substitution of fly ash and silica fume doses to concrete will affect the permeability and porosity of the concrete (Chaudhary & Sinha, 2020; Wang et al., 2022).

Figures 7 and 8 show the effect of curing concrete on the permeability coefficient (*k*). In fly ash concrete, substituting 20% and 30% fly ash for cement by immersion in seawater significantly increases the permeability coefficient. The matter means that replacing fly ash of that size with seawater will make the permeability coefficient of seawater into the concrete even more significant, up to 3.67 x 10^{-7} m/s.

In silica fume concrete, a similar situation occurred where adding 5% and 7% silica fume to concrete immersed in seawater increased the permeability coefficient up to 1.04 x10^{-7} m/s. This value shows that silica fume concrete has a better permeability value than fly ash concrete in this study.

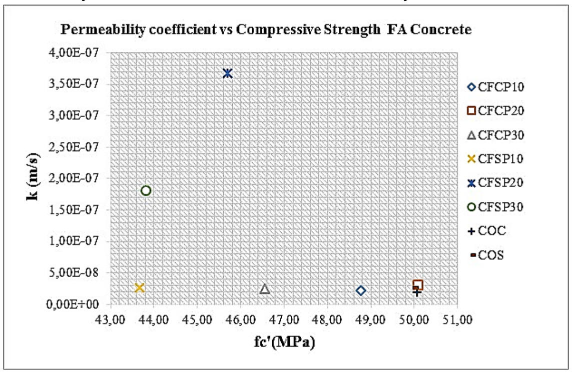

Figure 7. *k* vs *fc'* of fly ash concrete

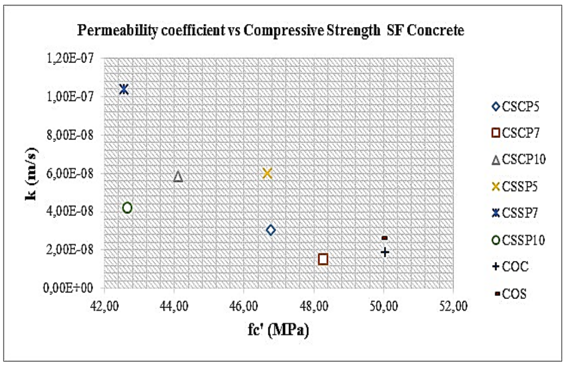

Figure 8. *k* vs *fc'* of silica fume concrete

The correlation between the compressive strength (fc') of the concrete and the permeability coefficient (k) of the concrete has a correlation coefficient of -0.631 (negative). The two data variables are closely related, but their correlation is negative, meaning that when the permeability coefficient rises, the compressive strength will also rise. This evidence demonstrates that when the permeability coefficient increases, concrete becomes more porous and loses compressive strength (Al-Lami, 2021; Anwar et al., 2022).

A similar trendline correlation between fc' and k is also shown in the research results by Ibrahim and Issa (2016), where the compressive strength depends on the permeability value.

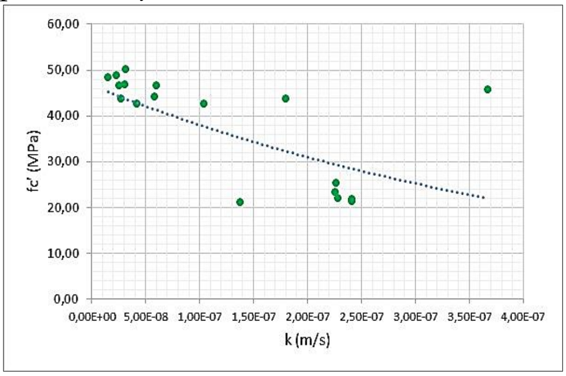

Figure 9. Correlation of *fc'* and *k*

Figure 10. Permeability test

In line with the results of this study, other researchers, such as Zhang and Zong (2014), conducted a study with the results obtained indicating that only surface water absorption is related to concrete performance, including permeability. The resistance and impermeability to the effects of sulfates are linearly related to the surface absorption of the concrete, and the correlation coefficient of the two variables is not less than 0.9.

The results of this study are also in line with research conducted by other researchers. Salain (2021) researched concrete with a high-volume fly ash mixture (ATVT). His research showed that the compressive strength, split tensile strength, and impermeability increased gradually with hydration time and reached those produced by concrete. The matter means that the more waterproof the concrete, the more compressive strength will increase.

Conclusion

Adding Fly Ash and Silica Fume as substitution materials for green concrete used in the marine environment can achieve and exceed the design quality of fc' 30 MPa. The average target fcr' compressive strength is 33.9 MPa. A compressive strength value of 36.65 MPa was attained by the 20% fly ash replacement concrete with freshwater treatment; however, after 90 days, the average compressive strength value exceeded the fc' and fcr' values by 55 MPa. In 20% fly ash substituted concrete with seawater treatment, the compressive strength value achieved at 90 days of concrete age is 50 MPa.

For concrete with Silica fume substitution, the best compressive strength value was achieved at a 5% substitution variation with freshwater treatment, namely 46.7 MPa at 28 days of age and increased to 49.4 MPa at 90 days of concrete. For concrete treated with seawater, the best compressive strength results were obtained at a 5% Silica fume substitution variation of 40.71 MPa at 28 days of age and increased at 90 days of concrete at 47.71 MPa.

Concrete has successfully attained the desired compressive strength in both normal ambient conditions and situations with seawater effects. When fly ash is added to freshly treated concrete, the penetration value is still below 5 cm, which satisfies the specifications. However, the fly ash substituted concrete with seawater treatment is more valuable than required.

The best replacement material for concrete in a marine environment is silica fume substitution concrete. It has a good water penetration value related to permeability, below 5 cm for all variations of adding and treating freshwater and seawater.

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