International Journal of GEOMATE, May, 2024 Vol.26, Issue 117, pp.100-107
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.117.g13257
Geotechnique, Construction Materials and Environment

WATER PENETRATION PROPERTY OF CONCRETE WITH COPPER SLAG FINE AGGREGATE

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ABSTRACT: Attempts have been made recently in Japan to use copper slag fine aggregate, a by-product of copper smelting, as a fine aggregate for concrete. Concerns indicate that copper slag fine aggregates could lead to material separation due to bleeding and contribute to steel corrosion. The 2017 Standard Specification for Concrete stated that the water penetration rate into the concrete must verify the steel corrosion associated with water penetration. However, a few studies have focused on the water penetration properties of concrete with copper slag fine aggregates, even though clarifying their water penetration properties is paramount. Thus, this study evaluated the water penetration rate coefficients of concrete with copper slag fine aggregate using the predicted values given in the specifications. In this regard, concrete was prepared with ordinary Portland cement, considering a replacement of 10 % and 30 % of copper slag fine aggregate in terms of fine aggregate volume and a replacement of 10 % and 20 % of fly ash in terms of binder mass for the 30 % replacement case. The results showed that the water penetration rate coefficient of concrete with copper slag fine aggregate could be evaluated using the prediction equation given in the Standard Specification for Concrete by the Japan Society of Civil Engineers. Moreover, the results indicated that the water penetration rate coefficient of the concrete decreases with increasing modulus of elasticity.

Keywords: Copper slag fine aggregate, Fly ash, Water penetration rate coefficient, Modulus of elasticity

1. INTRODUCTION

In recent years, copper slag fine aggregates, a by-product of copper refining, have attracted increasing attention in Japan as an alternative to sea sand regarding ecological impact and environmental protection [1]. In Japan, concrete with copper slag fine aggregate is frequently used in unreinforced concrete structures, such as wave-dissipating blocks; this aggregate is used in structures where high weight is an advantage. However, concrete with copper slag aggregate is more prone to bleeding than concrete with conventional fine aggregate, resulting in material separation. Moreover, a few examples of its use in reinforced concrete structures exist. Thus, the durability of concrete using copper slag fine aggregate should be clarified to expand the use of copper slag fine aggregate. Although previous studies have focused on the corrosion properties of rebars in concrete with copper slag fine aggregate [2], few studies have focused on moisture penetration properties.

The Japanese concrete structure design standards have indicated that the neutralization verification method of concrete is a leading factor contributing to steel corrosion in concrete [3]. Previous studies have shown that steel corrosion progresses due to water hanging. Studies have reported that the progress of neutralization in such locations is minimal. Consequently, studies have been conducted to evaluate water penetration into concrete [4,5]. In this regard, a verification method for steel corrosion due to neutralization and water penetration has been included in the Design Standard Part 2, "Durability Design and Durability Verification" of the Concrete Standard Specification (Design Part) (hereafter referred to as the "Specification"), which became effective in 2017 [6,7]. The specifications were revised and included again in 2022 [8]. Water penetration into the concrete must be evaluated when verifying steel corrosion due to water penetration. Although the specifications suggest a method for calculating a standard water penetration rate coefficient based on experimental results and using the water-binder ratio as a variable, few experimental studies on concrete with copper slag fine aggregate exist. Moreover, the characteristics of water penetration are not clear. In addition, when copper slag fine aggregate is used, fly ash is frequently mixed as a binder to suppress bleeding, which may segregate the material. Therefore, understanding the water penetration characteristics of concrete containing copper slag fine aggregate and fly ash could enable the use of copper slag fine aggregate for unreinforced concrete structures and reinforced concrete structures.

In this study, the durability of concrete with copper slag fine aggregate is investigated by evaluating the penetration rate coefficient of concrete using copper slag fine aggregate as a substitute for the fine aggregate and concrete with fly ash as a substitute for the binder. Moreover, the water penetration characteristics of this mixture were evaluated

2. RESEARCH SIGNIFICANCE

In this study, the durability of concrete with copper slag fine aggregates is investigated by evaluating the penetration rate coefficient of concrete with copper slag fine aggregate as a substitute for the fine aggregate and concrete with fly ash as a substitute for the binder and by evaluating these moisture penetration characteristics. The results show that the moisture penetration rate coefficient of concrete with copper slag fine aggregate can be evaluated using the prediction equation given in the specifications. Moreover, the results indicated that the water penetration rate coefficient of the concrete decreases with increasing modulus of elasticity.

3. OVERVIEW OF EXPERIMENT

3.1 Cases to Be Examined

Table 1 lists the cases considered in this study. The case with ordinary Portland cement (OPC) was set as the reference. In addition, the Japan Society of Civil Engineers (JSCE) points out in its publication [9] that when copper slag fine aggregate is used, the volumetric replacement of fine aggregate should be limited to 30 % or less. Also, in practice, fly ash is used as part of the binder to reduce bleeding. Therefore, CUS10 is a case where 10 % of the fine aggregate volume is replaced with copper slag fine aggregate, and CUS30 is a case where 30 % of the fine aggregate volume is replaced with copper slag fine aggregate. In addition, there are two cases based on CUS30: CUS30FA10, in which 10 % of the volume of the binder material is replaced with fly ash, and CUS30FA20, in which 20 % of the volume of the binder material is replaced by fly ash. Table 2 shows a list of the concrete mixtures used in each case. In this study, the design basis strength was set at 24 N/mm^2, and the water–cement ratio was kept constant at 53 %. The target slump was set at 8.0 cm. The details of the materials used are listed in Table 3. Crushed sand from Akou City, Hyogo Prefecture, was used as the fine aggregate, and CUS2.5 was used as the copper slag fine aggregate. Crushed stone from Osakakobashi, Itano-cho, Itano-gun, Tokushima Prefecture, was used as coarse aggregate. Fly ash II and an AE agent were used as the admixture materials.

3.2 Test Conditions

Air content (JIS A 1128), slump (JIS A 1101), bleeding (JUS A 1123), and setting (JIS A 1147) tests were conducted to determine the properties of the fresh concrete. In addition, compressive strength test (JIS A 1108) and static modulus of elasticity test (JIS A 1149) were conducted to determine the properties of the concrete after hardening, and the water penetration rate coefficient test (JSCE-G 582-2018) (hereinafter referred to as the water penetration coefficient).

The compressive strength, static modulus of elasticity, and water penetration rate coefficient tests were performed in accordance with JIS A 1132. After demolding, the specimens were cured in water for up to 28 d. The compressive strength and static modulus of elasticity were then tested. The specimens used for

Table 1 Five test cases of experiments

Case	S	CUS	C	FA
OPC	*s*	-	*B*	-
CUS10	0.9*s*	0.1*s*	*B*	-
CUS30	0.7*s*	0.3*s*	*B*	-
CUS30FA10	0.7*s*	0.3*s*	0.9*B*	0.1*B*
CUS30FA20	0.7*s*	0.3*s*	0.9*B*	0.2*B*

Where, S is fine aggregate, CUS is copper slag fine aggregate, C is cement, FA is fly ash, s is the fine aggregate volume and B is the binder mass.

Table 2 Table of specified mixture

		Density (g/cm³)	Surface dry density (g/cm³)	Water absorption rate (%)	F.M.
Crushed sand	S	-	2.58	1.60	
Crushed stone	G	-	2.57	1.60	7.04
Copper slag aggregate	GUS	-	3.51	1.12	2.82
Fly ash Ⅱtype	FA	2.33	-	-	2.61
Ordinary Portland	C	3.16	-	-	-
AE agent	AE	1.06	-	-	-

Where, d_{max} is the maximum size of the coarse aggregate, SI is the slump volume, Air is the air volume, W/C is the water cement ratio, s/a is the fine aggregate ratio, W is the unit water volume, C is the unit cement volume, FA is the unit fly ash volume, S is the unit crushed sand volume, CUS is the unit copper slag fine aggregate volume, G is the unit coarse aggregate volume, and Ad is the AE agent volume.

Table 3 Details of the materials used

Case	d_{max} (mm)	SI (cm)	Air (%)	*W/C* (%)	*s/a*	Unit value (kg/m^3)						A_d (cc/m^3)
						W	*C*	*FA*	*S*	*CUS*	*G*	
OPC	20	8	4.5	53.2	42.9	175	329	0	748	0	992	3560
CUS10	20	8	4.5	53.2	41.0	175	329	0	643	97.3	1020	3200
CUS30	20	8	4.5	53.2	43.2	175	329	0	527	307.0	986	2200
CUS30FA10	20	8	4.5	53.2	41.0	175	296	32.9	640	96.7	1020	3200
CUS30FA20	20	8	4.5	53.2	41.0	175	263	65.8	636	96.2	1010	3200

water penetration rate coefficient testing was cut and removed approximately 25 mm from the bottom end face at the time of casting, and then to 28 d. The compressive strength and static modulus of elasticity were then tested. The specimens used for the water penetration rate coefficient testing were cut and removed approximately 25 mm from the bottom end face at the time of casting and then accelerated dried for 28 d at a temperature of 40 ± 2 °C and a relative humidity of 30 ± 5 %.

After drying and curing, the dried specimens were immersed in water at a temperature of 20±2 ℃ with the cut side down, and the depth of water penetration was measured after 5, 24, and 48 h of immersion. The sides of the specimens were sealed with curing tape to ensure that the water permeated only from the cut surface. After the prescribed immersion time, the specimens were pulled out of the water and split in the center of the specimen in the vertical direction during immersion, and the water penetration depth of the two split specimens was measured. The measured water penetration depth was the average of three measurements taken immediately after each time point. A color developer was sprayed on the cracked surface of the specimen in according to NDIS 3423, and the coloring distance was measured using calipers of the two split specimens. The measured water penetration depth was the average of three measurements taken immediately after each time point.

4. RESULTS AND CONSIDERATION

4.1 Fresh Properties of Concrete

Fig. 1 shows the results of the bleeding test. Fig.2 shows the results of the setting test. The vertical axis shows the penetration resistance and the horizontal axis shows time. In addition, the initial setting resistance and final setting resistance are indicated by red lines in Fig.2. And Fig. 3 shows the results of the air content test, Fig. 4 shows the result of the slump test. Air contents were 4.5%, 3.1%, 4.8%, 6.6%, and 6.5% respectively, slumps were 2.8cm, 5.2cm, 6.3cm, 8.5cm, and 10.3cm respectively.

As seen in Fig. 1, similar to previous studies [10], the bleeding rate increased as the percentage of the replaced copper slag fine aggregates increased. This could be due to the fact that the unit volume weight of the copper slag fine aggregate was greater than that of the commonly used crushed sand aggregate. In addition, the bleeding rate of CUS30FA10 was approximately equal to that of CUS30. Furthermore, the bleeding rate of CUS30FA20 was higher than that

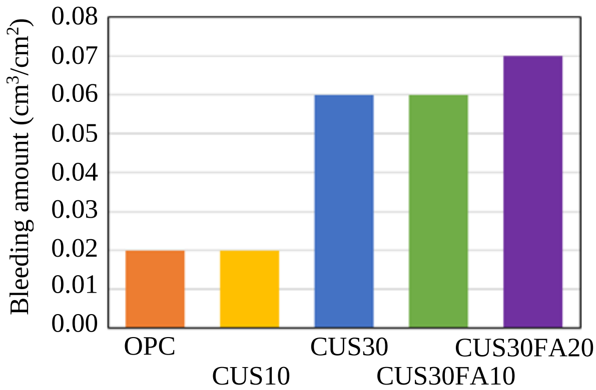


Fig. 1 Bleeding test results

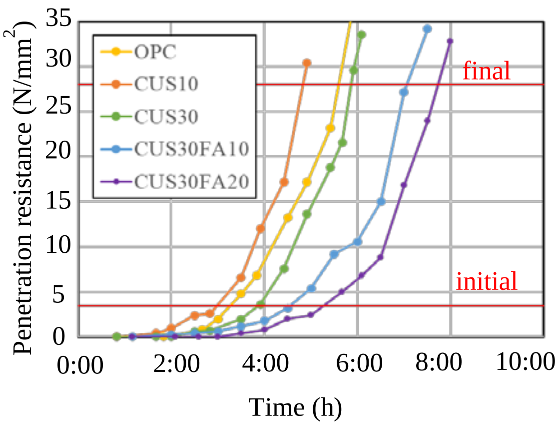


Fig. 2 Curdling test results

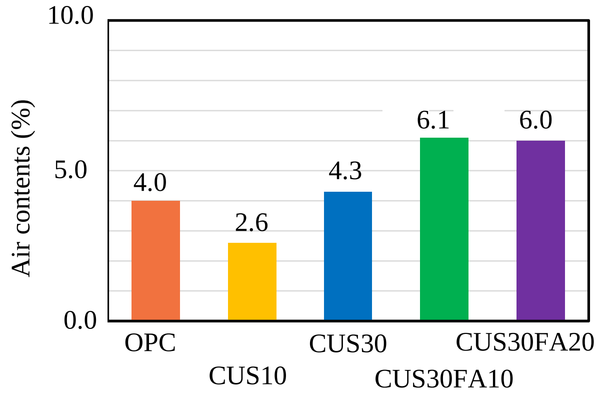


Fig. 3 Air content test results

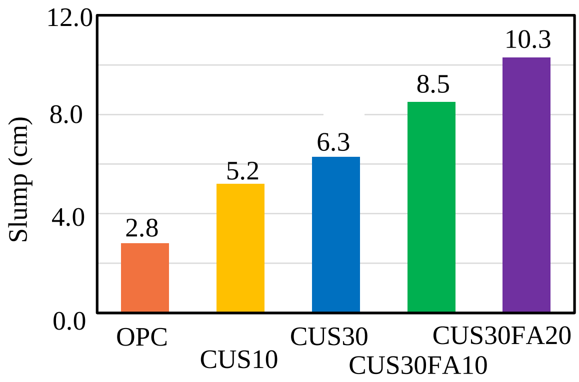


Fig. 4 Slump test results

of CUS30, and the bleeding suppression effect of the fly ash admixture could not be confirmed in this study.

Looking at the results of the curdling test shown in Fig. 2, it can be observed that the curdling times of OPC, CUS10, and CUS30 were slower, in that order. It is believed that this is due to the use of copper slag fine aggregate, which causes some material separation in the concrete due to bleeding, and delays the hydration reaction. In addition, the experimental results for CUS30FA10 and CUS30FA20 indicate that the curdling time was further delayed. This was attributed to the delay in strength development caused by the replacement of fly ash, in addition to the delay in the hydration reaction caused by material separation due to bleeding, as described above.

4.2 Mechanical Properties of Concrete

Fig. 5 shows the results of the compressive strength test 28 d after underwater curing. Fig. 6 shows the results of the modulus-of-elasticity tests. The results of the compressive strength test show that the OPC and CUS10 results were approximately the same, but the CUS30 results were approximately 4 % below average. Similar to the present study, previous studies [11] have shown that compressive strength tends to decrease when the percentage of copper slag fine aggregate replacement increases above a certain level. This is thought to be due to the fact that the water channels created by the bleeding caused by the use of copper slag fine aggregates form voids in the concrete, and that the adhesion between the copper slag and cement paste interface is reduced by the bleeding.

The compressive strength test results of CUS30FA10 and CUS30FA20 were approximately 22 % and 30 % below the average compressive strength test values, respectively. In addition to these factors, the use of fly ash as part of the binder reduced the amount of cement in the concrete, which led to a reduction in the hydration reaction and a delay in the initial strength development.

Also, looking at the results of the static modulus test shown in Fig. 4, it is observed that the static modulus of CUS10 was higher than that of OPC. However, overall, the static modulus of elasticity tended to decrease with the addition of copper slag fine aggregate and fly ash as binders.

As mentioned earlier, it is believed that this is because that the water channels created by the bleeding of copper slag fine aggregate form voids in the concrete, and that adhesion between the copper slag and the cement paste interface is reduced by the bleeding. The addition of fly ash as a binder delayed the onset of strength and stiffness.

4.3 Water Penetration Properties of Concrete

Fig. 7 shows the measurements of the water penetration rate coefficient. The vertical distance from the bottom of the concrete in the reddish-brown area of the figure was measured using calipers.

Figs. 8–12 show the results of the water penetration depth measurements over time. The vertical axis in the figures represents the penetration depth, L (mm), and the horizontal axis represents the square root of the elapsed time. From these figures, it can be seen that the slope of the approximate line obtained by the least-squares method corresponds to the water penetration rate coefficient.

When the water penetration velocity coefficient cannot be determined experimentally, the specifications allow the predicted value, q_p, of the water penetration velocity coefficient of concrete, as shown in Eq. (1), to be used in design verification. Equation (1) is expressed as a function of the water-binder ratio W/B, and can be calculated using the same equation for concrete commonly used in Japan, regardless of the type of binder, such as blast furnace slag fine powder or fly ash.

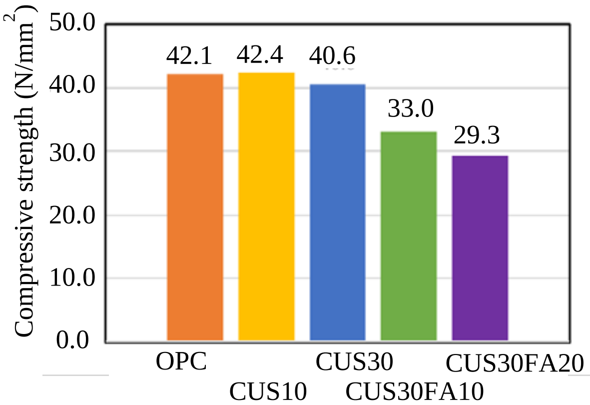


Fig. 5 Compressive test results

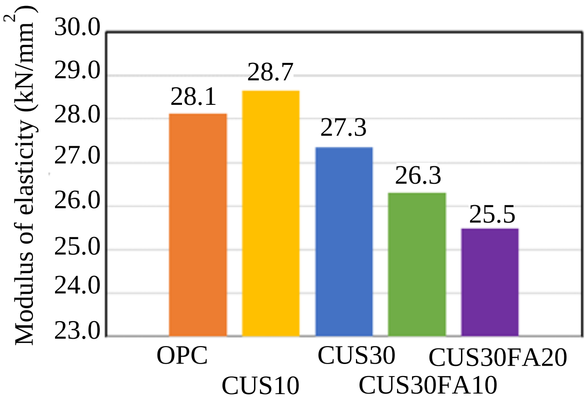


Fig. 6 Modulus of elasticity test results

$$q_p=31.25 \cdot (W/B)^2 \ (0.40 \leqq W/B \leqq 0.60) \qquad (1)$$

Since the water-binder ratio in this study was set at 0.53, the predicted water penetration rate coefficient calculated according to Eq. (1) is 8.77 mm/√hour.

Fig. 13 shows the water penetration rate coefficient for each case. The predicted water penetration rate coefficient of 8.77 mm/√hour calculated by Eq. (1) is represented with a solid red line in the figure, 6.18mm /√hour, 5.78mm /√hour, 6.48mm /√hour, 7.18 mm/√hour, and 6.24 mm/√hour, respectively. All of these values are lower than the predicted water penetration rate coefficient of 8.77 mm/√hour. In other words, in all cases in this study the probability of water penetration into the concrete was lower than the predicted value of the water penetration rate coefficient according to Eq. (1). This indicates that the water penetration rate coefficient value predicted in the specifications can be used when 30 % copper slag fine aggregate is mixed as part of the fine aggregate by volume substitution. In addition, when copper slag fine aggregate is used, fly ash, used to control material separation by bleeding, can be evaluated up to 20 % by mass using the predicted value of the water penetration rate coefficient.

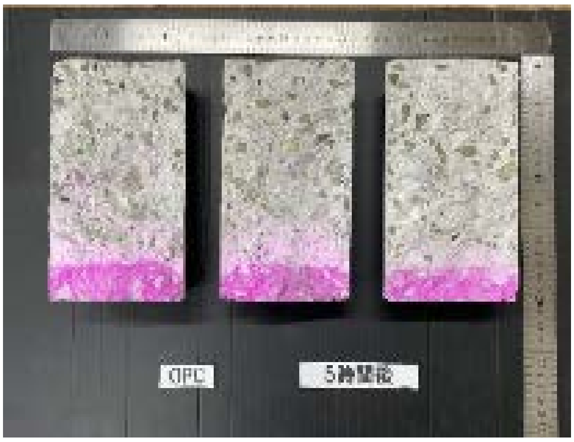
Fig. 14 shows the relationship between the elastic modulus and the water penetration rate coefficient. The vertical axis represents the water penetration rate coefficient, while the horizontal axis represents the modulus of elasticity. The figure indicates that the water penetration rate coefficient decreases as the modulus of elasticity increases. This is because the water penetration rate varies depending on the size and density of the voids in the concrete. Therefore, for dense concrete with few voids, the modulus of elasticity increases, whereas the water penetration rate coefficient decreases. The modulus of elasticity generally increases with increasing compressive strength. Thus, the experimental results suggest that increasing compressive strength decreases the water penetration rate coefficient.

However, the results for CUS30FA20 showed that the water penetration rate coefficient was 6.24 mm/√hour despite having the lowest modulus of elasticity, indicating that the water penetration rate coefficient does not tend to increase. This is because the use of fly ash retards the onset of compressive strength due to hydration and pozzolanic reactions, decreasing the modulus of elasticity. Moreover, as in previous studies [12], the fine particle content of fly ash reduces the voids in the pores of the concrete, improving the filling ability of the concrete and increasing the apparent water penetration rate. The apparent water penetration rate coefficient decreased by improving the filling properties of the concrete by reducing the voids in the pores. This phenomenon is evident in CUS30FA20, which was mixed with more FA. This result suggests that adding FA has led to a lower water penetration rate coefficient.

In other words, the use of FA as an admixture might reduce the compressive strength and modulus of elasticity at a young age compared to concrete without FA due to the hydration reaction and pozzolanic reaction relationship. However, the water penetration rate coefficient decreases due to the densification of the concrete interior by the effect of FA. However, the amount of fly ash in the mixture did not vary in many cases within the experimental range of this study. Thus, further investigation is required.

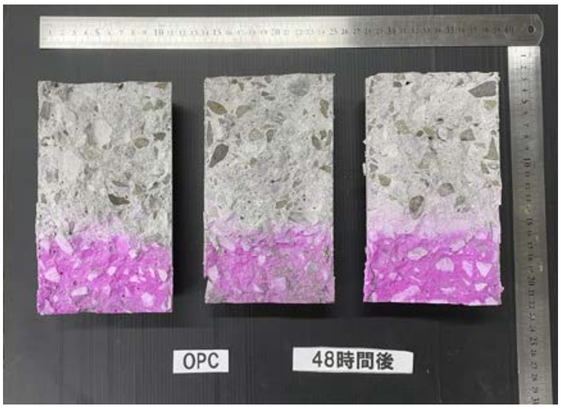
5. CONCLUSION

To extend the use of concrete with copper slag fine aggregate in reinforced concrete structures, water



(a) After 5 h

(b) After 24 h



(c) After 48 h

Fig. 7 Water penetration depth measurement

penetration rate tests were conducted in this study on concrete with copper slag fine aggregate and fly ash subjected to short-term water exposure. Consequently, the water penetration characteristics were evaluated by testing the water penetration rate in concrete subjected to short-term water exposure.

The following are the results obtained. Five cases were prepared and analyzed in this study. The results showed that concrete was prepared with ordinary Portland cement and a replacement of 10 % and 30 % of copper slag fine aggregate in terms of fine aggregate volume and a replacement of 10 % and 20 % of fly ash in terms of binder mass in the case of a 30 % replacement.

(1) The experimental results showed that the water penetration rate coefficients were lower than the formulas given in the Japanese Design Code, Specifications of Methods, in all cases. Therefore, the water penetration properties of concrete with fine copper slag aggregate can be evaluated using the same formula used for general concrete.
(2) The relationship between the modulus of elasticity and water penetration rate coefficient shows that the water penetration rate coefficient decreases as the modulus of elasticity of the concrete increases.
(3) However, for concrete mixed with a relatively large amount of fly ash, the water penetration rate coefficient showed no tendency to decrease when the modulus of elasticity increased. Thus, further investigation is required.

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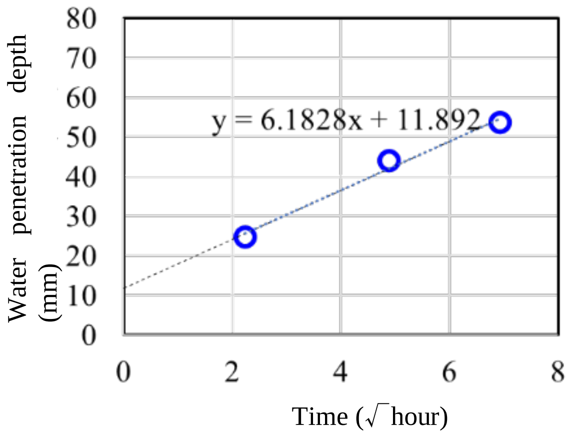

Fig. 8 Water penetration rate coefficient results (OPC)

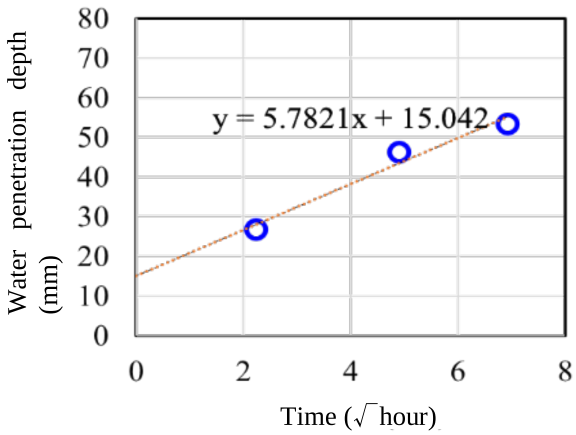

Fig. 9 Water penetration rate coefficient results (CUS10)

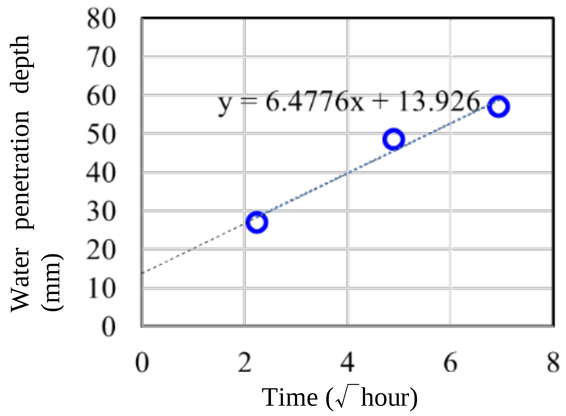

Fig. 10 Water penetration rate coefficient results (CUS30)

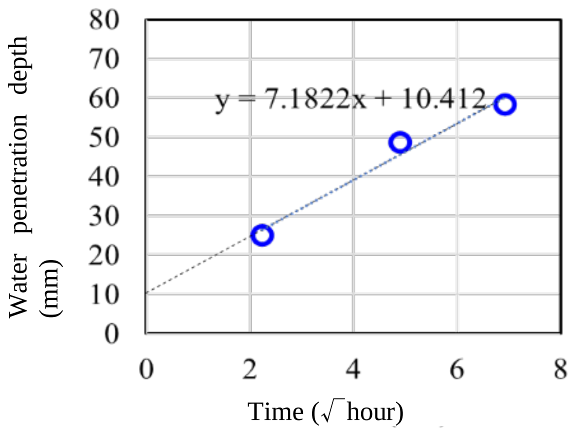

Fig. 11 Water penetration rate coefficient results (CUS30FA10)

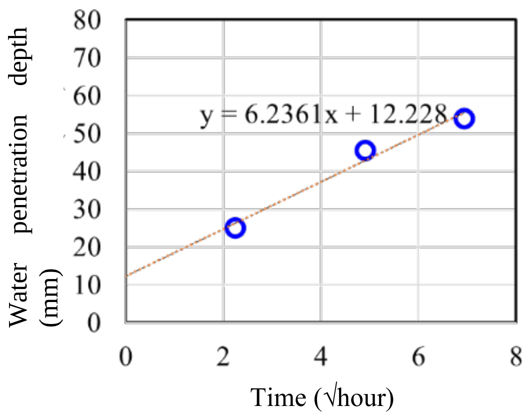

Fig. 12 Water penetration rate coefficient results (CUS30FA20)

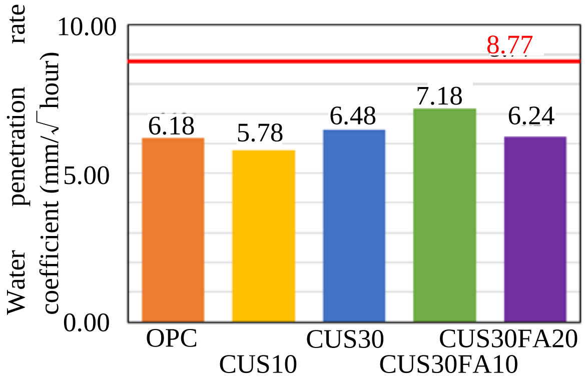

Fig. 13 Water penetration property coefficient (all cases)

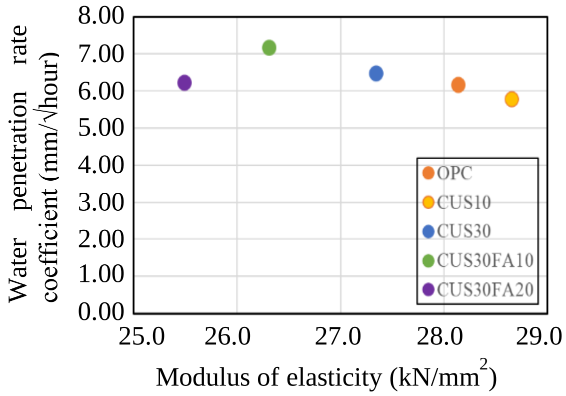

Fig. 14 Relationship between water penetration property coefficient and static modulus of elasticity

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