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Long-term Compressive Strength Properties of Concrete Incorporating Admixtures: Outdoor Exposure Testing in a Coastal Environment

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Abstract

In this study, concrete specimens were fabricated based on domestically manufactured materials, and long-term exposure tests were conducted in a domestic coastal environment. This study analyzes the long-term compressive strength characteristics of concrete mixed with admixtures. The mixed materials used were divided into blast furnace slag and fly ash. The blast furnace slag and fly ash were, respectively, produced by replacing ~ 30% and ~ 15% of the cement. The compressive strength was measured at 28 day, 1 year, and 10 years of age and compared with that of ordinary concrete. In addition, the long-term compressive strength results obtained in this study were compared with those of concrete mixed with admixtures reported in the literature. The strengths of the ordinary specimen at 1 year and 10 years of age increased by ~ 10 MPa and ~ 22 MPa compared with those at 28 day of age. However, concrete mixed with admixtures yielded compressive strength increases of ~ 5 MPa and ~ 26 MPa at 1 year and 10 years of age, respectively, compared with those at 28 day of age. A comparison of the compressive strengths of concrete mixed with admixtures reported in the literature (based on age) and those obtained in this study showed that there was an initial strength difference in the range of 10–25%. However, the compressive strength at 10 years of age was almost similar to those reported in the literature with differences of less than 5%. These findings confirmed that when using pozzolanic admixtures, the development rate of the initial strength may vary owing to various factors; however, the long-term strength converges within a certain range.

Keywords Long-term compressive strength, Water–cement ratio, Blast furnace slag, Fly ash, Outdoor exposure

1 Introduction

1.1 Outline

Concrete has remained the predominant construction material from historical times to the present, and it has been employed in numerous structures subject to a vast range of environmental conditions. However, the rapid acceleration of concrete's premature deterioration and aging, driven by various climatic shifts, such as intensified heat waves, heavy snowfall, and alterations in the structure's surrounding environment, is an increasing concern. This trend results in detrimental outcomes, such as escalating maintenance costs and reduction in service life (Irina et al., 2010; Nath et al., 2011; Thomas et al., 2004; Mustafa et al., 1994).

To address these issues, both domestic and international design standards have stipulated minimum compressive strengths based on exposure classes. These standards have been formulated within a framework that considers the environmental factors inherent to the structures' locations (KDS 14 20 40, Ministry of

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Construction & Transportation, 2022; MOLIT, 2021). Additionally, from a material standpoint, numerous studies have been conducted to enhance the durability of concrete. These studies utilize pozzolanic materials, such as fly ash, blast furnace slag, and silica fume, to densify the concrete's internal structure (Bilodeau et al., 1998; Chofore et al., 2023; Kim et al., 2016; Kouloumbi et al., 1994; Lee et al., 2016a, 2016b). In particular, when these admixtures are used, the durability of concrete increases and the compressive strength at long-term aging is enhanced by promoting latent hydraulic hardening (Lee, 2014; Oner et al., 2003).

However, the evaluations of these standards and materials predominantly rely on accelerated indoor testing to assess concrete durability and predict long-term performance. These indoor experiments, while practical, have limitations in accurately emulating real-world environmental factors such as geography, topography, and climate. Consequently, the laboratory-derived values may deviate from those measured during long-term exposure tests in real-world settings. Therefore, there is a growing need for studies that can provide comparative analysis and validation (KDS 14 20 40, 2022; MOLIT, 2021). Furthermore, despite the widespread use of various pozzolanic materials, such as fly ash and blast furnace slag in real-world applications, research on their long-term durability remains somewhat inadequate. This underscores the need for more comprehensive long-term studies to confirm their enduring resilience (Bilodeau et al., 1998; Kouloumbi et al., 1994).

Long-term concrete properties are a subject of continuous research in many countries. These properties aim to predict and validate concrete performance based on extended exposure experiments in real-world environments. For instance, in the United States, Washa and Wendt (Washa et al., 1975) investigated the long-term properties of concrete over approximately 50 years using a variety of cement types, formulations, and aggregates. Fukute and Hamada (Mohammed et al., 2003) conducted exposure tests in coastal environments for 20 years and examined the long-term durability of various concrete specimens with water admixture as a variable.

In particular, the performance of concrete with incorporated admixtures is an ongoing area of investigation. These studies examined the impact of material properties, such as chemical composition, particle size, and admixture fineness, and evaluated concrete performance when admixtures were substituted or incorporated to the maximum extent possible in place of cement. For instance, Oner (Oner et al., 2005; Oner et al., 2007) evaluated the performance of concrete using blast furnace slag powder and fly ash as admixtures and derived a time-dependent strength prediction model for concrete containing blast furnace slag powder. Hashimoto (Hashimoto et al., 2021) conducted a 40-year study on the long-term performance of concrete with approximately 70% blast furnace slag powder to cement ratio. Hwang (Hwang et al., 2004) investigated the long-term performance of concrete with fly ash based on a 1-year exposure test and subsequently derived a time-dependent strength prediction model.

In South Korea, these types of tests are predominantly conducted by public institutions owing to spatial and temporal constraints. The Korea Institute of Civil Engineering and Building Technology has been conducting research on the long-term performance of concrete since 2003 and exposure tests in both inland and coastal environments employing diverse concrete types (KICT, 2003, 2006; Lee and An., 2012). The Korea Expressway Corporation is also conducting a long-term study on the performance of roadway facilities subjected to freeze–thaw cycles and winter deicing agents (Lee et al., 2015, 2016a, 2016b). Kwon (Yoon et al., 2020; Park et al., 2018) initiated research on the long-term performance of concrete by producing various types of concrete with different materials. This research includes fabricating concrete that has undergone long-term tests and conducting outdoor exposure experiments in coastal environments. However, many of these studies were conducted for a period of 180 day (or less), with long-term concrete performance predictions based on these short-term performance outcomes, resulting in insufficient validation of the predictions.

To analyze the long-term properties of concrete in local conditions, this research focused on the fabrication of various concrete specimens utilizing materials exclusively produced and manufactured within South Korea. Furthermore, an assessment of these specimens' long-term properties was conducted based on exposure tests over a period of more than 10 years in the country's native environment. A focal point of this study is an analysis of the long-term compressive strength properties of concrete incorporating admixtures, namely, blast furnace slag and fly ash. The 10-year compressive strengths of these mixtures were then compared with that of ordinary concrete (Lee & Lee, 2023). Additionally, the long-term compressive strength results obtained from this study were analyzed and compared with those reported in the literature that used concrete with incorporated admixtures.

1.2 Analysis of Literature

In this study, we reviewed existing studies on the long-term strength characteristics of concrete mixed with admixtures. The trends were analyzed by comparing them with the data obtained from this study.

First, we compared the strength models of ordinary concrete derived under the same environmental conditions to analyze the long-term properties of concrete with admixtures. In addition, domestic and international standards and literature were reviewed and compared.

The KICT compressive strength model (Lee & Lee, 2023) is an empirical-based strength prediction model derived based on ~ 15 years of exposure of ordinary concrete to the domestic environment. The KICT compressive strength model was derived by regression analysis of the logarithmic model. The listings, a and b, in Eq. (1) are constants based on the water/binder ratio; these were derived using experimental data. Therefore, in this study, the KICT model equation with the same water/binder ratio was used for comparison with concrete mixed with admixtures. That is, the compressive strength according to age was obtained based on the KICT model equation with a water/binder ratio of 50% and was then compared with the results obtained in this study.

$$y = a \cdot \ln(t) + b, \tag{1}$$

where $a = 4.9536\, and\, b = 41.839 (water/binder\, ratio\, 50\%)$.

To analyze the long-term properties of concrete with admixtures, we compared domestic and international standards. However, while domestic and international standards provide a time-dependent compressive strength model for ordinary concrete, they do not present a model for concrete with admixtures. Consequently, the compressive strengths obtained from the prediction models of plain concrete established in these standards were compared with the compressive strength derived in this study. For South Korea, the prediction model equation (KDS 14 20 01) from the concrete structural design standard was employed. For international standards, models established by the American Concrete Institute (ACI 209R-92), European Concrete Board (CEB-FIP), and Japanese Society of Concrete Engineers (JSCE) were used (KDS 14 20 40, Ministry of Construction & Transportation, 2022; ACI 209R-92, American Concrete Institute Committee209, 1997; CEB-FIP, 2010; JSCE, 2007).

Second, a review of domestic and international literature on the long-term characteristics of concrete mixed with admixtures was conducted. The admixtures were limited to blast furnace slag or fly ash. Because of limited data from the literature that are identical to the conditions of this study (water/binder ratio, amount of admixture), data were collected regardless of the water/binder ratio and amount of admixture. The compressive strength data were collected and organized, including more than 1 year of data, and compared with the data obtained from this study (Mohammed et al., 2003; Hwang et al., 2004; Yoon et al., 2020; Park et al., 2018; Shariq et al., 2010; Bilim et al., 2009; Abdelkader et al., 2010; Papadakis et al., 1999; Kanta et al., 2022; Sivasundaram et al., 1990; Naik et al., 2003; Hooton et al., 2013; Liu et al., 2014; Kumar et al., 2008; Yoshitaka, 2015; Mohan Malhotra et al., 2000). In total, 26 data points were obtained by age for concrete mixed with blast furnace slag, whereas 44 data points were obtained for concrete mixed with fly ash.

2 Material and Methods

2.1 Mix Design

The specimen used in this study was fabricated in 2008 and subsequently underwent an exposure test that lasted approximately 10 years in a domestic coastal environment. The mixture was prepared with a water-to-binder ratio of 50%, and incorporated blast furnace slag powder and fly ash as admixtures. The specific mix design is presented in Table 1. The cement used was type-1 ordinary Portland cement based on the Korean standard KS L 5201 (in Korean). For the specimen incorporating blast furnace slag admixture (BS), 30% of the cement was replaced by the slag. In the case of the specimen with fly ash admixture (FA), 15% of the cement was substituted. The properties of the utilized materials are presented in Tables 2 and 3.

2.2 Specimen Fabrication

The specimen incorporating blast furnace slag and fly ash was formed into a cylindrical shape with dimensions of 100 × 200 mm. After pouring the concrete, it was subjected to a 2-day wet cure, followed by a 26-day dry cure. On the 29th day, the specimen was transferred to an outdoor exposure test site to commence the exposure test.

Table 1 Mix design of concrete

Type	Water/binder ratio (%)	Fine aggregate ratio (%)	Unit weight (kg/m^3)					
			W	C	Coarse aggregate	Fine aggregate	Blast furnace slag admixture (BS)	Fly ash admixture (FA)
BS50	50	42	175	245	1020	730	105	–
FA50	50	42	175	297.5	1020	730	–	52.5

Table 2 Properties of binder

Type	Main components (%)					Density (g/cm^3)	Fineness (cm^2/g)
	SiO_2	Al_2O_3	MgO	SiO_3	CaO		
Ordinary Portland cement	21.01	6.40	3.02	2.14	61.33	3.15	3,413
BS	33.33	15.34	5.70	2.08	42.12	2.90	4,159
FA	55.3	25.8	0.8	0.3	2.9	2.18	3,550

Table 3 Properties of fine and coarse aggregates

Type	Gmax* (mm)	Specific gravity (g/cm^3)	Water absorption (%)	Fineness modulus (FM)
Fine	–	2.56	2.62	2.59
Coarse	25	2.64	0.82	6.87

* Coarse aggregate maximum size (Gmax): when sieving with 5 mm (standard sieve 4.75 mm) during a sieve test, the aggregate that remains (> 85%) is referred to as coarse aggregate, and this term refers to the maximum size of this aggregate

The compressive strength was measured in accordance with the Korean standard KS F 2405 (in Korean).

2.3 Experiment Method

The outdoor exposure test site was situated near Gochang-gun, Jeollabuk-do, approximately 60 m from the coast. The site's average annual maximum and minimum temperatures were 37 ℃ and − 13.9 ℃, respectively, as shown in Fig. 1. The average number of rainy days over 10 years was approximately 122, and the rainfall intensity ranged from a minimum of 0.1 mm/h to a maximum of 74.4 mm/h.

3 Compressive Strength Results

3.1 Compressive Strength by Age

Fig. 2 shows a summary of the compressive strengths (by grade) according to the type of mix. The strength of ordinary Portland cement (OPC) is depicted as the value derived from the prediction model discussed in Equ (1). For the OPC specimen, the compressive strength at 28 day was 29.5 MPa, which is less than that of the specimens with admixtures. The 1-year compressive strength exhibited an increase of approximately 10 MPa compared with the 28-day compressive strength, whereas the 10-year compressive strength exhibited an increase of approximately 22 MPa relative to the 28-day strength.

The specimen that incorporated BS exhibited a compressive strength of 32.7 MPa at 28 day of age, with an approximate increase of 4 MPa in the compressive strength at 1 year of age compared with the 28-day strength.

Similarly, the specimen with FA exhibited a compressive strength of 29.6 MPa at 28 day of age, which increased by approximately 5 MPa at 1 year of age compared with the 28-day compressive strength. The 10-year strength was 59.5 MPa, which corresponds to an increase of approximately 25 MPa compared with the 28-day compressive strength.

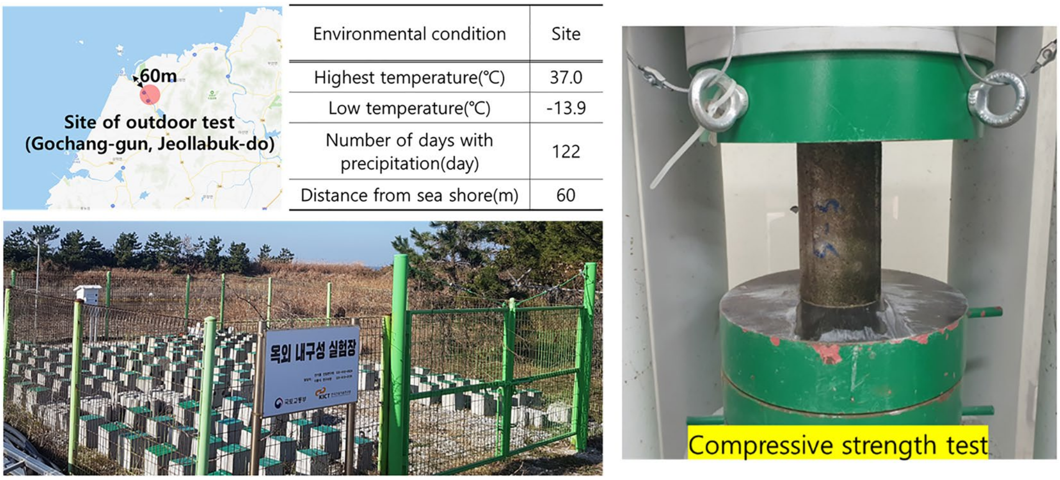
With respect to the specimens that incorporated BS and FA, it appeared that the pozzolanic material properties primarily affected the long-term strength rather than the initial strength. This resulted in a lower 1-year strength than that of the reference specimen. A more detailed analysis of this behavior across different age ranges is presented in Sect. 3.2.

3.2 Rate of Increase of Compressive Strength According to Age

This section evaluates the rate of increase in compressive strength based on the findings presented in Sect. 3.1. Fig. 3 shows the rate of increase in compressive strength in the specimens that incorporated BS and FA across different age ranges. In the figure, the short-term denotes the percentage increase in compressive strength at the age of 1 year compared with the 28-day strength, whereas the long-term represents the growth in compressive strength at the age of 10 years relative to the 1-year strength.

For the OPC specimen, the compressive strength growth from 28 day to 1 year was approximately 31%. For the specimens with admixtures, the increment was significantly lower at ≤ 15%. Specifically, the BS and FA specimens exhibited strength increases of ~ 12% and 13%, respectively.

For the comparison of the strength increase at the age of 10 years relative to the 1-year strength, the OPC exhibited a strength growth rate of 33% compared with that at 28 day. However, the concrete specimens with admixtures demonstrated a strength increase rate that exceeded 50%. Specifically, the BS and FA specimens exhibited strength increase rates of ~ 59% and 53%, respectively.



Environmental condition	Site
Highest temperature(℃)	37.0
Low temperature(℃)	-13.9
Number of days with precipitation(day)	122
Distance from sea shore(m)	60

Fig. 1 Site of outdoor test and experimental test setup photograph

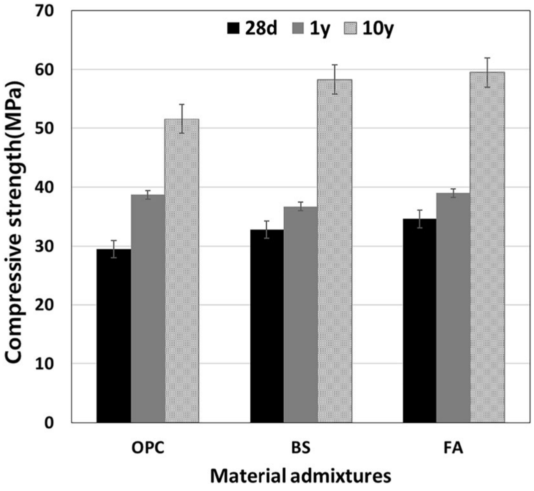


Fig. 2 Compressive strengths of the specimens

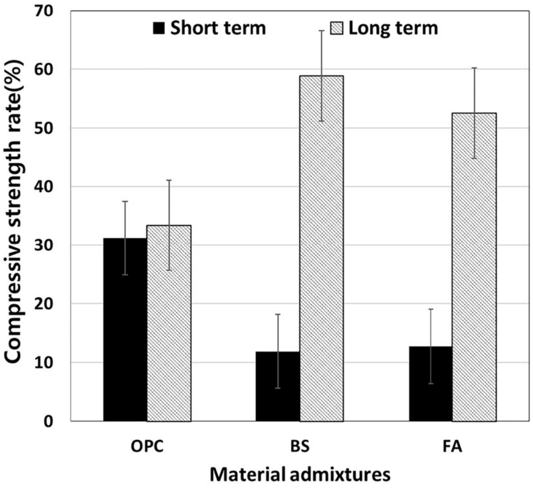


Fig. 3 Rate of increase of compressive strengths of concrete according to the ages of the specimens

The reason for the lower rate of increase in the short-term strength of the admixture specimen compared with that of the OPC likely stems from the SiO_2 content of the admixture, which is approximately 1.5–2 times higher than that of OPC. That is, SiO_2 reacted with $Ca(OH)_2$, a hydration by-product, to produce C-S–H hydrates, and this chemical reaction caused a delay in the development of the initial strength (Oner et al., 2005; Oner et al., 2007; Hashimoto et al., 2021; Hwang et al., 2004). Consequently, although the short-term strength increase rate of concrete with admixtures was lower than that of the OPC specimen, the rate of increase in the long-term strength was approximately 1.6 times that of the standard concrete. This growth rate is nearly five times higher than the short-term strength increase of concrete with the same admixture.

3.3 Comparison with Existing Predictive Models

Fig. 4 shows a comparison of the compressive strength values derived in this study with domestic and international standards. Fig. 5 shows a graph of the compressive strengths recorded by age based on the admixture test specimens from domestic and international studies along with the compressive strengths derived in this study. Notably, the domestic and international standards in Fig. 4 are the predictive models developed for ordinary concrete. As these standards did not include

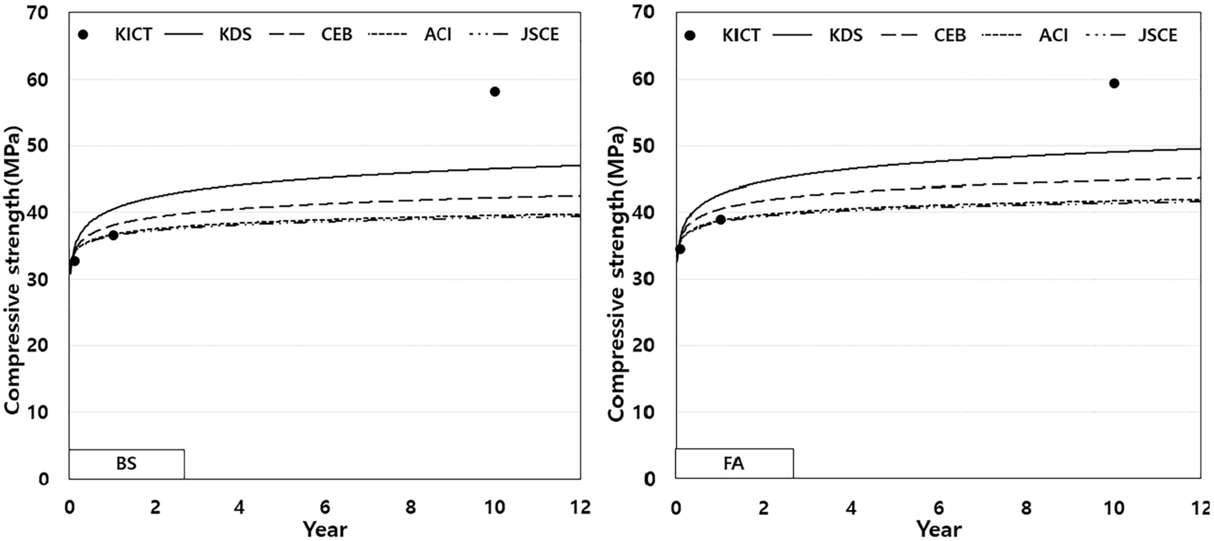


Fig. 4 Comparison of compressive strength of domestic and international standards

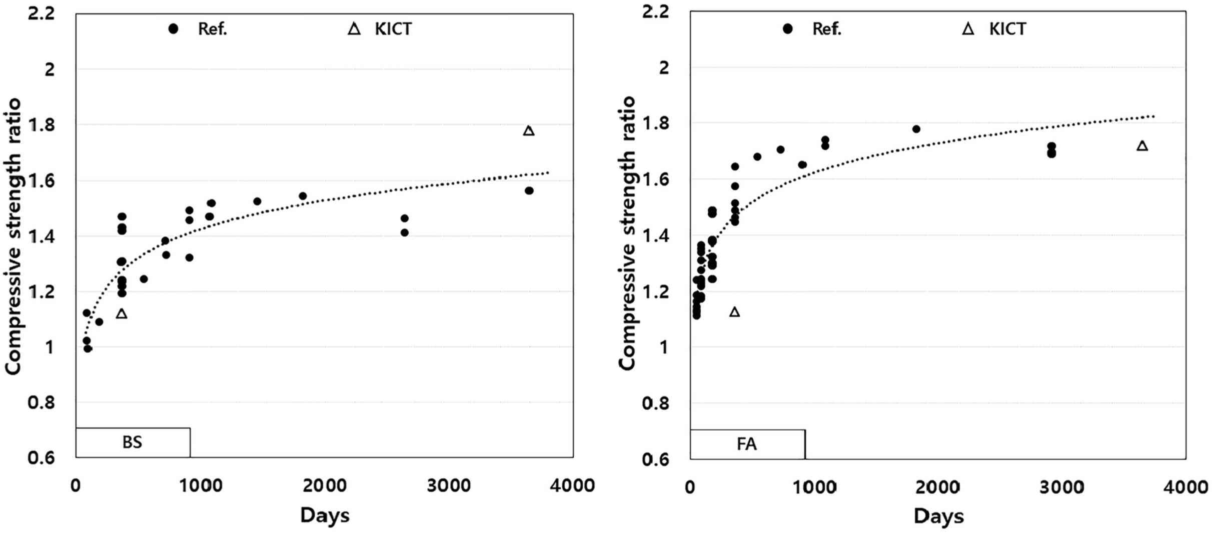


Fig. 5 Comparison of compressive strength results obtained from the literature

predictive models for concrete with admixtures, the predictive model for ordinary concrete was used.

3.3.1 *Comparison of Compressive Strength Prediction Models of Domestic and International Standards*

Fig. 4 illustrates the actual compressive strength values measured in this study juxtaposed with the compressive strengths of domestic and international standards (three types). The vertical axis represents the compressive strength at time "t," whereas the horizontal axis represents the age in years.

The analyzed results indicate that the predicted values closely aligned with the domestic and international standard predictions at 1 year of age regardless of the type of admixture, whereas at 10 years, the predicted values were as high as 1.5 times compared with those of the domestic and international standards. For the specimen with BS, the measured 1-year strength of 36.7 MPa was lower than the predicted values of the domestic and international standards, with the highest being the KDS predicted value of 42.2 MPa. However, the 10-year compressive strength measured in this study was the highest, surpassing the values suggested by other standards by at least 20% and up to 52%.

The results for the FA specimen paralleled those for the blast furnace slag powder specimen. At 1 year of age, the measured value for the fly ash specimen was 39 MPa, which is comparable to the lowest value in the domestic and international reference values. At 10 years of age, the measured value peaked at 59.5 MPa, which is higher than those of the domestic and international standards by 25–70%.

The discrepancies between the domestic and international standards and the measured values in this study can be attributed to the fact that the concrete assessed in the domestic standards was mixed with OPC. Notably, the BS and FA used in this study were pozzolanic materials, which affected the long-term strength more than the initial strength. These are features that were not accounted for in the domestic and international standards. Furthermore, the disparity between the experimental results in this study and the domestic and international standards allows for comparisons of the differences in the trends of compressive strength over time between ordinary concrete and concrete incorporating admixtures. It will be essential to develop diverse predictive models for concrete that are made by either incorporating admixtures (used in the field) or cement with more than two components and to establish a process to verify them.

3.3.2 Comparison with Experimental Results in the Literature

Fig. 5 shows the compressive strength by age based on literature data presented in Sect. 1.2. The compressive strength measured in this study is also shown. The x-axis of the graph represents age, whereas the y-axis represents the compressive strength measured by age divided by the compressive strength at 28 day. Additionally, a trend line is plotted in Fig. 5 based on the total experimental data.

The analyzed results reveal that the specimen with BS deviated by approximately 10% from the trend line regardless of age. In contrast, the specimen with fly ash exhibited a 25% difference at 1 year of age and approximately 5% difference at 10 years of age. It is postulated that these discrepancies are due to the impact of the chemical composition of the blast furnace slag and fly ash used in this study, as well as material characteristics such as fineness, and environmental conditions, such as the exposure environment. These factors affect the activity index of the blended materials and the initial strength of the concrete. Nevertheless, despite these differences, the compressive strength measured at 10 years of age in this study only varied by approximately ± 5% from the trend line drawn from the results of the existing literature. From these observations, it can be inferred that variations in initial strength may arise because of differences in the water–binder ratio and the mixed amount of binder. However, the long-term age strength values can converge within a certain range. Therefore, it is anticipated that ongoing data acquisition and verification will be essential in future studies.

4 Conclusions

In this study, we fabricated specimens with admixtures and conducted long-term exposure tests in domestic environments. The following conclusions are drawn regarding the compressive strength properties based on the findings of this study.

- Comparison of compressive strengths at different ages revealed that the specimens incorporating blast furnace slag and fly ash exhibited an increase of 4–5 MPa in compressive strength at 1 year of age compared with that at 28 day of age. Furthermore, at 10 years of age, the compressive strength increased by approximately 25–26 MPa compared with the strength at 28 day.
- Analysis of the rates of increase of strength according to the age range and admixture type indicated that the increase rate from 28 day to 1 year of age was 11–12% regardless of the admixture. However, at 10 years of age, the rate of increase was ~ 59% for specimens that incorporated blast furnace slag and ~ 53% for specimens with fly ash.
- A comparison of the strength characteristics of ordinary concrete and concrete with admixtures based on domestic and foreign compressive strength standards and the measured values in this study revealed that ordinary concrete exhibited a rapid strength increase up to 1 year of age. In contrast, concrete with admixtures exhibited a lower initial strength increase rate; however, they demonstrated significant increases in strength at higher ages.
- Comparisons of the long-term compressive strengths measured in this study and the results obtained from existing studies on concrete with incorporated admixtures revealed that the strength at 1 year of age exhibited a difference of approximately 25% from the trend line drawn based on existing experimental values. However, the strength at 10 years of age fell within the error range of the trend line.
- This study highlighted the strength trend of concrete over time by targeting mixed materials commonly used in the field. Therefore, it is expected that the findings of this study will be used to derive a strength prediction model for concrete mixed with admixtures in the future. In addition, the results from

this study can be used as basic data of the strength characteristics and long-term strength trends when mixing admixture materials during onsite casting. Additional research is needed for this. In follow-up research, the long-term effects of various ratios of admixtures and the strength characteristics according to environmental conditions will be evaluated.

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Author contributions
The first author, BL, conducted the experiments, performed data analyses, and wrote the manuscript. The corresponding author, JSL, supported the writing of the paper and shared in the final revision. JSR prepared the research plan and supervised the experimental work. All authors read and approved the final manuscript.

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Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

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