AN EXPERIMENTAL STUDY ON THE VARIATIONS IN MECHANICAL PERFORMANCE OF CONCRETE COMPONENTS

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Abstract - The performance of reinforced concrete members is a consequence of factors such as the material variability of concrete, variation of the water/binder ratio (W/B), and binder type. The performance of concrete members is greatly influenced by the compressive strength, tensile strength, and elastic modulus of the concrete, which plays a dominant role in the performance variation compared to other factors. Various experimental studies have been carried out on the variability of concrete materials. However, studies on the mechanical properties according to the mixing characteristics have been undertaken from various viewpoints. In this study, we investigated the mechanical properties, compressive strength, and elastic modulus of concrete according to the W/B ratio, binder type, and binder replacement ratio. In particular, we evaluated and compared the mechanical characteristics of ternary blended concrete with separate application of fly ash (FA) and blast furnace slag (BFS) each and the simultaneous application of both FA and BFS. The results of this study show that the FA is excellent not only in the initial expression rate but also in the long-term strength. In contrast, the blast furnace slag powder showed a low expression of initial strength intensity, but the expression of its long-term intensity increases with age. However, the strength expression characteristics of fly ash are generally superior to those of blast furnace slag powder. Furthermore, as mentioned above, the characteristics of the ternary blended concrete are similar to those of blast furnace slag powder. In addition, the results of evaluating the relationship between compressive strength and elastic modulus revealed that their relationship was almost constant regardless of the W/B ratio, admixture type, and admixture replacement rate. The results of this study indicate that the elastic modulus of concrete can be effectively derived from the compressive strength.

Index Terms - Concrete, Mechanical Properties, Ternary Blended

I. INTRODUCTION

There is a growing interest in nuclear power generation for efficient energy production and utilization. In contrast, concerns about the safety of nuclear power plants have also increased. Therefore, it should be verified that the structural materials used to construct power generation structures enable efficient design while first securing safety. Nuclear power generation structures requiring safety are mostly made of concrete. Concrete is a composite material consisting of various components such as cement, aggregate, and admixture, and has to be verified for applicability according to the required function and use environment of the target structure.

Korean nuclear technologies have been recognized globally in recent years, and there is growing interest in exporting energy technology to developing countries. To promote the export of Korean nuclear technologies, more concrete performance evaluation data is required for the concrete used in the structures [1]. In particular, evaluation of the characteristics of the structural members comprising the structures is essential to evaluate the structural performance [2-3].

Considering that the time it takes to construct a structure takes up a substantial portion in the construction period of a nuclear power plant, and the amount of construction materials required for the construction of structures is enormous, it is necessary to develop high performance technology for concrete as the main material of the nuclear power plant structures in order to shorten the construction period and save costs.

Recently, the development and field applications of ternary blended concrete (TB) prepared by mixing blast furnace slag (BFS) powder and fly ash (FA) with class 1 ordinary Portland cement (OPC) are increasing, to improve durability and reduce the hydration heat of large civil engineering structures [4-5]. Moreover, basic research on the mechanical performance has been actively conducted [6]. Construction companies have been making efforts continuously to shorten the construction period to reduce construction costs. To achieve this goal, the early strength performance of concrete is required. Therefore, it is necessary to improve the performance of ternary blended concrete (TBC), which is relatively slow in expression of early strength. In this study, as an attempt to improve the early strength expression performance of TBC mortar, the compressive strength, SO_3 content and SEM(scanning electron microscope) of mortar were analyzed by adjusting the fineness and addition rate of blast furnace slag powder and anhydrous gypsum.

In this study, the optimum admixture (blast furnace slag powder, fly ash and ternary blended concrete) replacement rate and mixing conditions are proposed through the analysis of the adequacy of high performance concrete premixing and the experiment and analysis of mechanical characteristics. The results of these analyses will be used appropriately in the selection of the specification mix for higher performance concrete in the future.

II. OUTLINE OF EXPERIMENT

2.1 Used Materials and Mixture

Type 1 cement with a specific gravity of 3.15 was used as the binder for concrete production. In addition, for the mineral admixture, fly ash and blast furnace slag powder were used, which are currently being used for the construction of nuclear power plants. Their specific gravities were 2.15 and 2.2, respectively. For fine aggregates, river sand with a specific gravity of 2.55 and a fineness modulus of 2.8 was used. For coarse aggregates, crushed stones with a maximum size of 20 mm and a specific gravity of 2.55 were used. The specific gravity value of each material is outlined in Table 1.

Table 1 Specific gravity of each material

	Cement	Fly ash	Blast furnace slag powder	Fine aggregates	Coarse aggregates
Specific gravity	3.15	2.15	2.2	2.55	2.65

A preliminary experiment was carried out with a total of 12 mixes using the materials in Table 1. These 12 mixes include the standard mix (OPC) using only the ordinary cement as binder, a mix with fly ash (FA), mixes with blast furnace slag powder (BFS), mixes with both fly ash and blast furnace slag powder, and a comparative mix for reviewing the performance change according to the changed unit quantity. The mixing ratios of the 12 mixes are listed in Table 2.
In Table 2, the first number of the mix name signifies the water/binder (W/B) ratio and the English letters after the number indicate the binder type and mixing ratio. Furthermore, the number after a dash in the last two mixes indicate the changed unit quantity.

Table 2 Concrete mix table

Mix	W/B (%)	Water	Replacement ratio(%)		
			Cement	FA	BFS
35OPC	35	155	100	0	0
35FA20	35	155	80	20	0
35BS50	35	155	50	0	50
35TB	35	155	50	20	30
40OPC	40	155	100	0	0
40FA20	40	155	80	20	0
40BS50	40	155	50	0	50
40TB	40	155	50	20	30
30FA20	30	155	80	20	0
30BS50	30	155	50	0	50
40FA20 -145	40	145	80	20	0
40FA20 -165	40	165	80	20	0

* FA: Fly Ash, BFS: Blast Furnace Slag, TB: FA+BFS

2.2 Experiment Details and Variables

In this study, the W/B ratio was fixed at three values (30%, 35%, and 40%), and the mineral admixtures for binder were fixed tot two types (fly ash and blast furnace slag powder). The ratio of fly ash was fixed at 20% of the binder weight and the ratio of blast furnace slag powder at 50% of the binder weight. However, the ternary blended mix contained 20% of fly ash 20% and 30% of blast furnace slag powder. To examine the reactivity of the blast furnace slag powder, its activity index was measured in accordance with the test method in ASTM C 989. For this purpose, 50 mm ×50 mm ×50 mm mortar specimens were fabricated and their compressive strength was measured at 7 and 28 days of age. Furthermore, to compare the performance according to the changed unit quantity, the performance variations were examined by using the unit quantity as a variable (145 kg/m^3, 155 kg/m^3, 165 kg/m^3).

The slump and air content, which are required to achieve constructability and durability, were fixed considering the required performance. The slump was determined in the range of 13 cm to 19 cm, considering the increased viscosity because of the addition of admixture. The air content was determined in the range of 3.5% to 6.5%, to provide durability. In addition, to determine the hardening property of each mix, the initial setting time and final setting time of each mix were compared. To understand the mechanical characteristics of the hardened concrete, the compressive strength and elastic modulus of concrete were measured. The performance was compared between 7 and 28 days of age. The details of experiment and variables are outlined in Table 3.

Table 3 Details and variables of experiment

Measured items	Standards	Experimental variables
Slump	ASTM C 143	Fixed (13–19cm)
Air Content	ASTM C 231	Fixed (3.5–6.5%)
Setting time	ASTM C 191	For each mix
Compressive strength & Elastic Modulus	ASTM C 39 ASTM C 469	- W/B ratio: 30, 35, 40% - Admixture replacement rate: FA (20%), BFS (50%), TB (20%+30%) - Unit quantity (145 kg/m^3, 155 kg/m^3, 165 kg/m^3) - Reviewed age: 7 and 28 days

III. BASIC EXPERIMENTAL RESULTS

3.1 Setting Test Result

The setting results for each binder are listed in Table 4. The results show that as the W/B ratio increased, the initial setting time and final setting time increased.

The reason for this seems to be the delayed reactivity due to the reduction of binder. To examine each case in more detail, when only cement was used as binder, the initial setting started between 5:00 and 5:30; however, the final setting was completed between 7:00 and 8:00. In other words, it progressed rapidly from the initial setting to the final setting, which corresponds to the case of using OPC.

Table 4 Setting time (hour: minute)

Mix	Initial Setting time	Final Setting time
35OPC	5:00	7:00
35FA20	7:45	10:30
35BS50	5:30	8:30
35TB	7:00	10:00
40OPC	5:30	8:00
40FA20	8:00	11:00
40BS50	6:00	9:30
40TB	7:30	12:30
30FA20	7:15	10:15
30BS50	4:30	8:00
40FA20-145	8:00	12:00
40FA20-165	7:30	10:00

In contrast, when fly ash was mixed. The initial setting time was greatly delayed from 7:00 to 8:00, and the final setting time occurred between 10:00 and 12:00. This seems to be due to the slow initial reaction because fly ash is a pozzolan material whose initial reaction is slow and suggests that initial curing could be important when fly ash is used. However, when the unit quantity was changed, the initial and final setting times increased if the unit quantity increased because it increases binder quantity even with the same W/B ratio.

When the blast furnace slag powder was used, the initial setting time was between 5:00 and 6:00, and the final setting time was completed between 8:30 and 9:30. This represents a slow setting compared to OPC, albeit a much fast setting time compared to fly ash. This suggests that the initial reactivity of blast furnace slag powder is active, and this initial activation will be beneficial for early strength expression despite mineral admixture because it contributes to the initial strength. However, the ternary blended concrete that was prepared by mixing fly ash and blast furnace slag powder shows similar results to the case of fly ash and seems to be greatly affected by fly ash.

3.2 Evaluation of Admixture Activity

As mentioned above, the blast furnace slag powder used in this study was considered to have high reactivity, and its activity index was evaluated according to the test method in ASTM C 989. The water/binder ratio satisfying the consistency proposed in ASTM C 989 was measured at 43%, and the activity index was examined by measuring the compressive strength by age. The results are listed in Table 5.

In this study, the activity index was evaluated based on 7-day strength. To compare the results, the activity index was 0.81, which is higher than0.75 proposed in ASTM C 989, although it is lower than 0.95. Therefore, the blast furnace slag powder was evaluated as being grade 100.

Table 5 Activity index of blast furnace slag powder

Specimen	Age	Measurement value (MPa)			Average	Activity index
OPC	7 days	2.16	4.18	3.68	3.34	-
BFS	7 days	2.94	2.52	2.71	2.72	0.81

IV. RESULTS AND CONCLUSION

In this study, the compressive strength and elastic modulus of specimens were measured according to age and mix, and the performance was evaluated based on the measurement result. To compare the strength expression by age using the average values of compressive strength, they are shown in Figs. 1 to 3.

4.1 Strength characteristics by water/binder ratio

4.1.1 OPC as binder

The strength characteristics for using OPC as binder are shown in Fig. 1. As this figure shows, the compressive strength increased with age, and it increased greatly as the W/B ratio decreased. However, based on the characteristics of the general ordinary Portland cement, the strength increase after 28 days is considered to be small, and it will be difficult to expect additional strength increase.

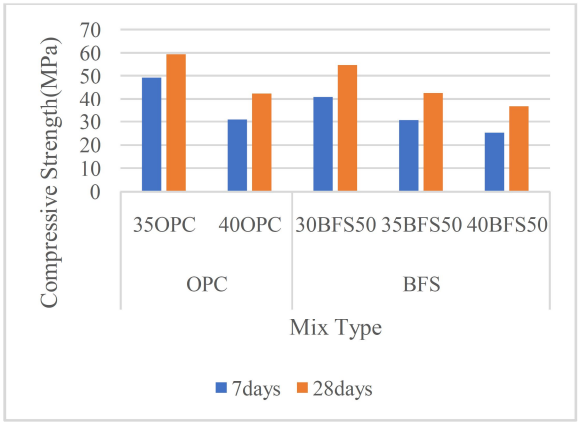


Figure 1. Compressive Strength (OPC & BFS)

4.1.2 BFS as binder

In this study, the strength variation characteristics when using a binder in which 50% of OPC and cement is replaced with blast furnace slag powder. The results are summarized in Fig. 1.

First, blast furnace slag powder has potential hydraulicity, which starts to react when calcium

hydroxide is formed by cement hydration and the inside of concrete is in alkali environment. Thus, its reaction is slower than the reaction of general cement, but faster compared to the above-mentioned fly ash, and can contribute to the long-term strength.

The results in Fig. 4.1 show the linear change of compressive strength according to the W/B ratio, suggesting that the strength expressions occur with increasing age.

4.1.3 FA as binder

The strength variation characteristics following the use of the binder that had replaced 20% of the OPC and cement weight with fly ash were examined, and the results are summarized in Fig. 2.

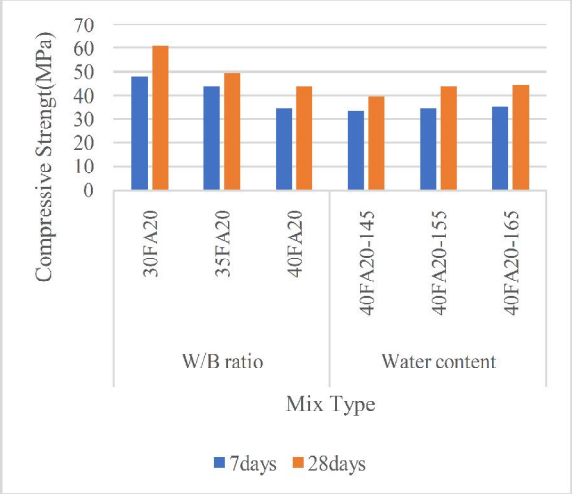


Figure 2. Compressive Strength(FA)

The concrete strength varied almost linearly according to the W/B ratio. Particularly when the strength by age is examined, strength expression was occurring continuously unlike the OPC. This result is due to the pozzolan reaction in the pozzolan materials such as fly ash and the long-term strength is expected to increase further. However, the factor that has been pointed out as having the greatest effect on the concrete strength in many studies is the W/B ratio. Because the W/B ratio actually determines the concrete strength, it was expected that the strength would not change much by unit quantity. However, the results show that the lowest compressive strength was measured in the mix with the smallest unit quantity, and the largest long-term strength was measured in the mix with the largest mix quantity. This result seems to be caused by the decrease of workability and unit binder quantity in the lowest unit quantity of 145 kg/m^3. In the unit quantity of 165 kg/m^3, it was caused by a large pozzolan reaction that occurred because of the relatively large content of fly ash.

4.1.4 Ternary blended material (OPC+FA+BFS) as binder

Ternary blended binders are widely used as part of the effort to reduce cement hydration heat. In this study, the applicability of ternary blended binder was examined considering the hydration heat issue. The composition of the ternary blended binder applied in this study consisted of fly ash for 20% of the binder quantity and blast furnace slag powder replacing 30% of the binder quantity. The results are summarized in Fig. 3.

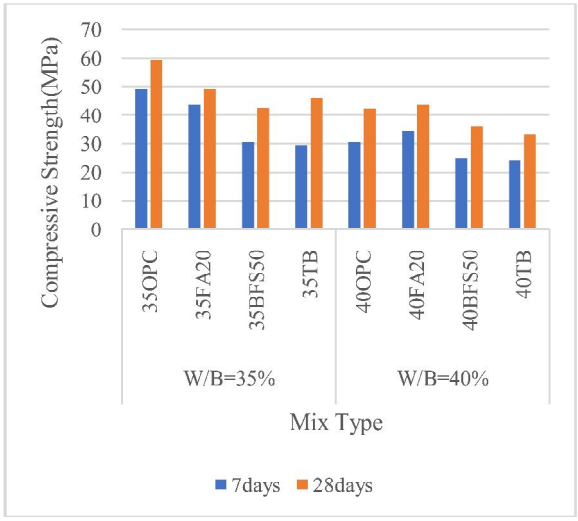


Figure 3. Compressive Strength (OPC, FA, BFS, TB: W/B = 35, 40)

In the case of the ternary blended material, the results are shown until 28 days of age because of the short progress time of the experiment; moreover, W/B ratios of only 35% and 40% were applied.

The results in Fig. 3 show that the strength expression rate and compressive strength are very similar to the those of the above-mentioned blast furnace slag powder. In other words, fly ash and blast furnace slag powder were applied simultaneously; however, the compressive strength expression characteristics were greatly affected by the blast furnace slag powder. The long-term strength expression characteristics are also expected to be similar to those of the blast furnace slag powder.

4.2 Elastic modulus characteristics by mix

Besides the compressive strength, which is the most important material constant of concrete structures, the factor that can determine the static and dynamic behaviors of a structure is the elastic modulus. The elastic modulus can be determined through the stress-strain curve of each material. For elastic modulus, a secant elastic modulus, a sine elastic modulus, and tangent elastic modulus can be used. Therefore, in this study, the secant elastic modulus, which is mainly used to analyze the behavior characteristics of concrete structure, was adopted. When the compressive strength was tested, LVDTs(linear variable differential transformer) were installed in both sides of the specimen and the specimen displacement was measured according to load reaction. For this load-displacement relationship, the average value was selected by using three

specimens under the same conditions, and the average was selected. The results are shown in Figs. 4 – 6.

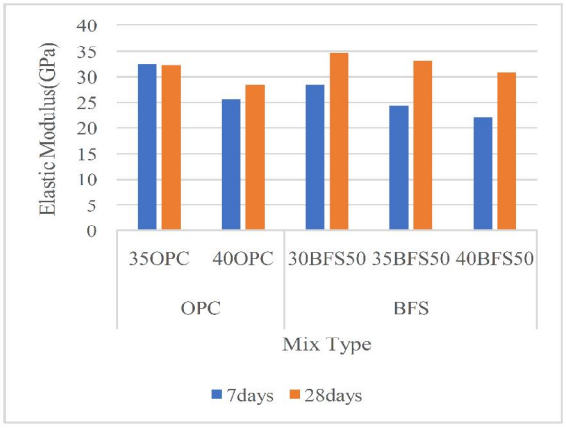


Figure 4. Elastic Modulus (OPC & BFS)

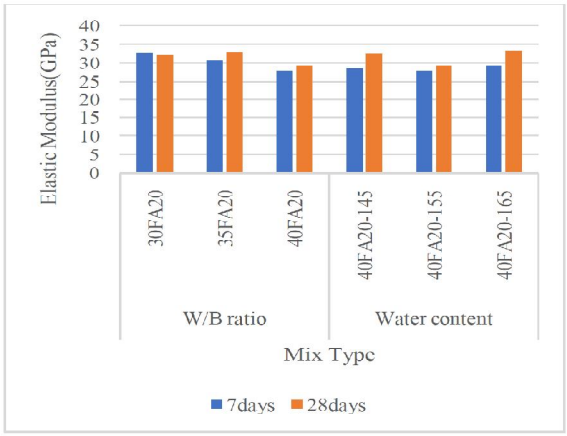


Figure 5. Elastic Modulus (FA)

The concrete elastic modulus is generally expressed as a function of compressive strength, and many research institutes and researchers have proposed the relationships equation. Therefore, in this study, the KCI equation proposed in the concrete structure design standard was compared with the data measured in this study. All the measurement data can be represented as Fig. 7.

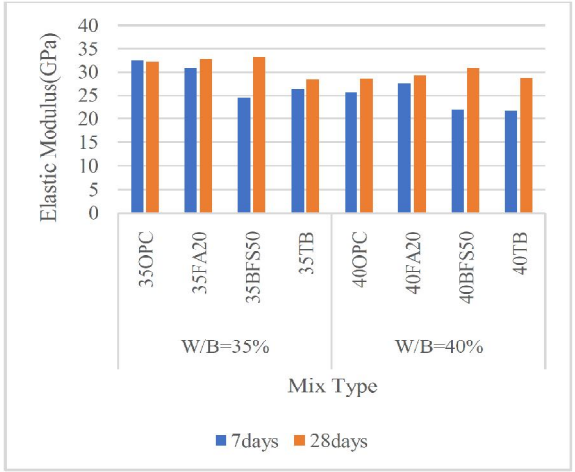


Figure 6. Elastic Modulus (OPC, FA, BFS, TB: W/B = 35, 40)

Figure 7 indicates that a constant relationship is maintained regardless of the W/B ratio, admixture type, and the admixture replacement rate. In other words, it is expected that the elastic modulus can be effectively derived from the compressive strength of concrete and it coincides well with the KCI equation used in the current concrete structural design standard.

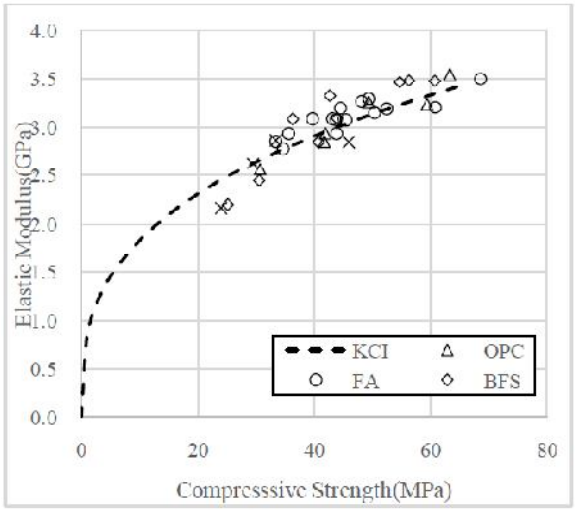


Figure 7. Compressive Strength vs Elastic Modulus

ACKNOWLEDGMENT

This work was supported by a Nuclear Power R&D Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. 20161510300420)

REFERENCES

[1] M. F. Kaplan, "Flexural and Compressive Strength of Concrete as Affected by the Properties of Coarse Aggregate", ACI Journal, vol.56, pp.1193–1208, 1959

[2] American Concrete Institute, "Design for Effects of Creep, Shrinkage and Temperature in Concrete Structure," ACI SP-27, American Concrete Institute,1971

[3] R. M. Christensen, "Mechanics of Composite Materials," Wiley Interscience, New York, 1979

[4] V. Y. Garas, K. E. Kurtis, "Assessment of methods for optimising ternary blended concrete containing metakaolin," Magazine of Concrete Research, no. 60, pp 499-510, 2008.

[5] G. Menéndez, V.Bonavetti, E. F.Irassar, "Strength development of ternary blended cement with limestone filler and blast-furnace slag," Cement and Concrete Composites, no. 25, pp 61-67, 2003.

[6] S. V.B. Reddy, D. P. R. Srinivasa, "Experimental studies on compressive strength of ternary blended concretes at different levels of micro silica and ggbs," Materials Today: Proceedings,no. 3, pp 3752-3760, 2016.

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