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Influence of Fly Ash on Strength Development of Concrete and its Temperature Dependence

Hiromi Yanokura[1], Isao Kurashige[2], Naoyuki Sugihashi[1], Keiichi Takahashi[3] and Yasuhiro Kuroda[3]

[1] Shimizu Corporation, Civil Engineering Technology Division, No.16-1, Kyobashi 2-chome, Chuo-ku, Tokyo, 104-8370, Japan, h-yanokura@shimz.co.jp, n-sugihashi@shimz.co.jp

[2] Central Research Institute of Electric Power Industry, Civil Engineering Research Laboratory, 1646 Abiko, Abiko-shi, Chiba, 270-1194, Japan, kurasige@criepi.denken.or.jp

[3] Shimizu Corporation, Research Institute, No.4-17, Etchujima 3-chome, Koto-ku, Tokyo, 135-8530, Japan, keichi.takahashi@shimz.co.jp, y.kuroda@shimz.co.jp

Abstract. *Experiments on the development of compressive strength and static and dynamic Young's moduli were performed by the following mix proportions of concrete: the first uses different types of Portland cement without fly ash (FA) with a water-cement ratio of 45%, keeping at different curing temperatures; the second partially use FA in place of the cement, with the other conditions same as above; the third uses only blast furnace cement B instead of Portland cement. With these specimens, we comparatively examined in terms of temperature adjusted concrete age, how the mechanical properties change with the use of cement only, FA replacement for cement and with variation in curing temperatures. As a result, it was confirmed that the replacement of cement by fly ash enhanced the long-term mechanical properties of concrete regardless of the curing temperature applied in this experiment.*

Keywords: *Fly Ash, Curing Temperature, Compressive Strength, Static Young's Modulus, Dynamic Young's Modulus.*

1 Introduction

Recently, in Japan, fly ash (FA) has been often used as a mineral admixture of concrete from the viewpoint of effective use of industrial waste and reduction of carbon dioxide (CO_2) emissions. (Takafumi, 2014) The use of FA as an admixture in concrete is said to be effective in improving concrete performance such as increasing workability of concrete, reducing thermal cracks, development of long-term strength, and suppressing salt damage and alkali-silica reaction. For this reason, in overseas countries, in particular in Asian countries, the trend of effective utilization of FA for concrete has become active due to the increasing number of coal power plants, because FA can be obtained at low cost as industrial waste. The pozzolanic reaction peculiar to FA is activated beneficially to develop the strength of concrete as the curing temperature increases. On the contrary, when the curing temperature is low, the strength enhancement due to the pozzolanic reaction does not progress and, in some cases, the expected effect may not be obtained.

Therefore, in order to understand the temperature dependency of the mechanical properties of the concretes using FA, three kinds of Portland cements which are partially replaced with FA were comparatively studied in terms of the impact by temperature on the development of mechanical properties of concrete. Note that we obtained basic data on the mechanical properties of cement types and curing temperatures in order to make full use of the effect of fly ash used in place of cement.

2 Experiment Plan

2.1 Outline of the Experiment

Regarding the use of cements and FA, one case is that different mix proportions for concrete are prepared at curing temperatures of 5, 10, 20, and 30°C, using only normal Portland cement (N), moderate heat Portland cement (M), or low heat Portland cement (L) respectively with no FA, and another case is that the mix proportions are prepared in the same condition as above, except 30 % of the proportion of the cement was substituted by FA. The specimens of concrete prepared were tested to obtain the strength development (for the case of N, 15% substitution of FA was also applied). For comparison, a mix proportion using blast furnace cement B instead of cement was used in the experiment.

2.2 Materials and Mix Proportions

Table 1 shows the list of materials used, Table 2 the quality of FA, and Table 3 the mix proportions (blending). The FA used is JIS A 6201 FA II class product from Noshiro Thermal Power Plant, and water to binder ratio (W/B) is set to be constant at 45%. Limestone fine powder (LP) was used to stabilize the fresh properties of mix proportions (blending) with the FA replacement ratio of 30%.

Concrete mixing was carried out in an environment of 20 ± 3 ℃ using a horizontal biaxial forced mixing mixer with a nominal capacity of 100 liters. The target slump 60 minutes after the concrete is mixed up was 18.0 ± 2.5 cm, the target air content was 5.5 ± 1.5%, and the rates of air-entraining water reducing agent (AD) and air-entraining agent (AE) were determined by test kneading.

Table 1. List of materials used.

Material	Symbol	Name and quality
Binder	N	Normal Portland cement Density 3.16 g/cm^3
	M	Moderate heat Portland cement Density 3.21 g/cm^3
	L	Low heat Portland cement Density 3.22 g/cm^3
	BB	Blast furnace cement B Density 3.04 g/cm^3
Mineral admixture	FA	Fly ash Density 2.19 g/cm^3
	LP	Limestone fine powder Density 2.70 g/cm^3
Fine aggregate	S	Limestone crushed sand Surface dry condition density 2.67 g/cm^3
Coarse aggregate	G	Limestone crushed stone Surface dry condition density 2.70 g/cm^3
Chemical admixture	AD	AE water reducing agent
	AE	AE agent (the agent for FA is used for FA concrete.)

Table 2. Quality data of FA.

Test item		Test result
Silicon dioxide（%）		66.6
Moisture（%）		0.1
Ignition loss（%）		2.0
Density（g/cm^3）		2.19
Fineness	Specific surface area by Blaine method（cm^2/g）	3,880
Flow value ratio		104
Activity index （%）	Concrete age 28 days	86
	Concrete age 91 days	100

2.3 Test Items and Methods

Test items and test methods are shown in Table 4. Specimens were taken after confirming that the slump and air content satisfied the target values at a test of fresh concrete 60 minutes after the mixing. After curing 24 hours in an initial curing room at a temperature of 20 ± 2°C with a relative humidity of 95% or more, the specimens were removed from their forms to be cured in the water at specified temperature conditions until specified ages when the specimens were subjected to various tests.

3 Test Results and Discussions

3.1 Test Results of Fresh Concrete

Table 5 shows the test results of fresh concrete. At every mix proportion, the slump and air content after 60 minutes met the targets. Remarkably, the mix proportion with 30% FA replacement, despite the high use of AE agent, recorded a more than 0.5% decrease in air content presumably due to unburned carbon of FA. In particular, the mix of LF30 had an extremely high decrease of 2.4% in air content.

Table 3. Mix proportion of concrete.

Symbol	W/B (%)	s/a (%)	Slump (cm)	Air content (%)	Unit weight (kg/m^3) Water W	Cement				Mineral admixture		Aggregate		Chemical admixture (%)	
						N	M	L	BB	FA	LP	S	G	AD	AE
N	45.0	44.0	18.0	5.5	165	367	—	—	—	—		780	1004	0.90	0.003
M						—	367	—	—	—		782	1007	0.80	0.003
L						—	—	367	—	—		782	1007	0.75	0.002
BB						—	—	—	367	—		774	997	0.80	0.003
NF15					160	303	—	—	—	53		782	1004	0.93	0.007
NF30					155	241	—	—	—	103	62	757	974	1.23	0.029
MF30							241	—	—	103	62	758	976	1.30	0.026
LF30						—	—	241	—	103	62	759	976	1.10	0.023

Table 4. Test items and methods.

Test item	Test method	Description
Slump	JIS A 1101	Tested 5 minutes and 60 minutes after being mixed up
Air content	JIS A 1128	
Mass of unit volume	JIS A 1116	
Concrete temperature	JIS A 1156	
Compressive strength	JIS A 1108	Tested at the age of 7 days, 28 days, 56 days, 91 days, 182 days, 364 days
Static Young's modulus	JIS A 1149	
Dynamic Young's modulus	JIS A 1127	

Table 5. Test results of fresh concrete.

Sym-bol	Slump (cm)		Air content (%)		Mass of unit volume (kg/m^3)		Concrete temperature (°C)	
	5 min	60 min	5 min	60 min	5 min	60 min	5 min	60 min
N	20.0	19.5	6.1	5.7	2324	2319	21	21
M	18.5	20.0	6.5	6.7	2303	2296	19	19
L	21.5	20.5	6.3	6.1	2312	2309	19	19
BB	19.5	20.0	4.9	5.3	2333	2322	19	19
NF15	18.0	18.0	5.3	5.4	2325	2315	21	21
NF30	18.0	17.5	7.1	6.5	2255	2277	21	21
MF30	17.0	20.0	7.0	6.5	2263	2279	21	21
LF30	19.5	18.5	8.5	6.1	2282	2294	22	21

3.2 Relationship between Age and Compressive Strength

Figure 1 shows the relationship between age and compressive strength for each mix proportion. The strength at the age of 7 days of the mix proportions using only Portland cement without FA increased in the order of N> M> L, and the higher the curing temperature, the faster the development of strength. However, at a high curing temperature of 30°C, their increase of strength tended to slow down in an earlier stage: N peaked after age 28 days; M after 56 days; L after 91 days. On the other hand, it was observed that all the mix proportions with FA replacement for cement did not reach the peak and still continued to develop their strengths. The substitution of FA for cement demonstrates a high effect on strength increase.

The compressive strength of BB at the age of 7 days varied largely due to curing temperature, and at the temperature of 30°C, was equivalent to N, and at 5°C equivalent to M, with a large difference from the mix with Portland cement without FA. At the curing temperature of 30°C, the growth in strength of BB slowed down after 56 days of age.
On the other hand, the strength for mix proportions with FA developed in the order of NF15> NF30> MF30> LF30, and grew for a long period regardless of differences in binder type and curing temperature.

3.3 Relationship between Temperature Adjusted Concrete Age and Compressive Strength

The strength development of concrete is closely related with the maturity (time considering temperature ingredient) (Fuminori *et al.*, 1991), and this tendency is more pronounced for the case of a mix proportion using FA (pozzolan material). We studied on the relationship between temperature-adjusted concrete age (te) and compressive strength (f) (CEB, 1990) which are shown in Equation (1); maturity law.

$$t_e = \sum_{i=1}^{n} \Delta t_i \cdot \exp\left[13.65 - \frac{4000}{273 + T(\Delta t_i)}\right] \tag{1}$$

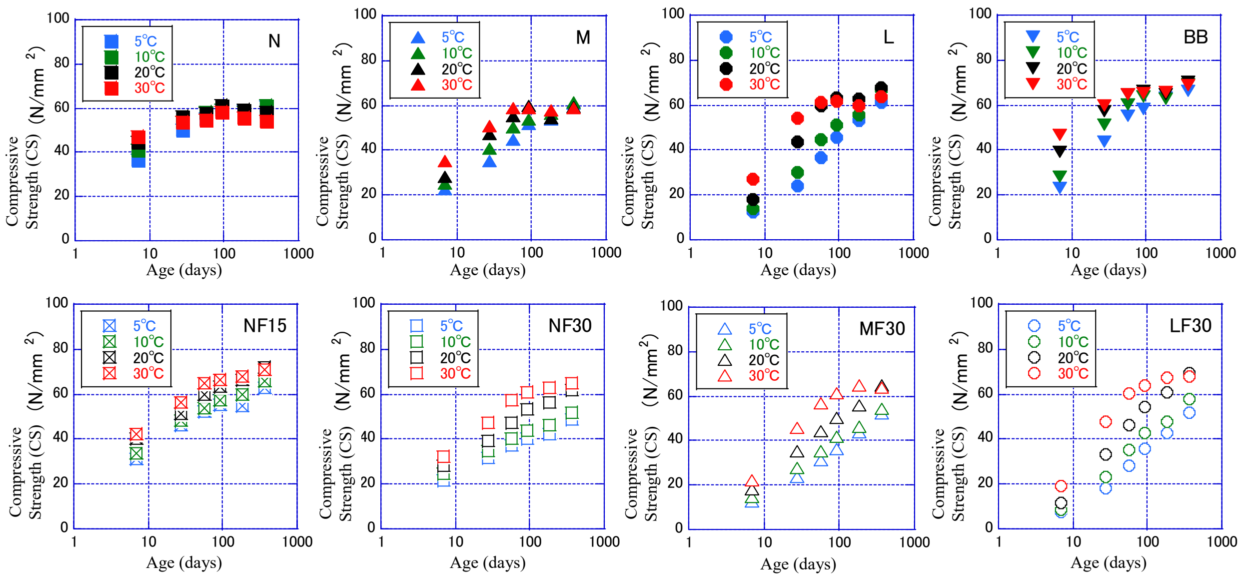

Figure 1. Relationship between concrete age and compressive strength in each mix.

Figure 2 shows the results of the relationship between temperature-adjusted concrete age and compressive strength for each mix proportion. The results of the regression analysis using Equation (2) are shown in Table 6 and Figure 2.

$$f(t_e) = a \cdot \log_{10} t_e + b \tag{2}$$

For N, M, L and BB, the data were regressed in the range with high linearity. "a" and "b" are regression coefficients obtained from experimental results.

Figure 2 indicates that the relationship between temperature adjusted concrete age and compressive strength for the mix proportions using FA keeps linearity for one year, while the relationship not using FA has limited linearity up to 91 days, from which we learn that strength development by FA continues for a long span of time. In the case of N without FA, the long term strength peaks at 60N/mm^2, while NF15 with 15% of cement replaced by FA still keeps increasing its strength even at about 80 N/mm^2, and NF15 with 30% replaced by FA does not peak even at 65N/mm^2. In the case of N, it was discovered that the effect of strength increase was greatly enhanced by about 15% replacement of cement by FA.

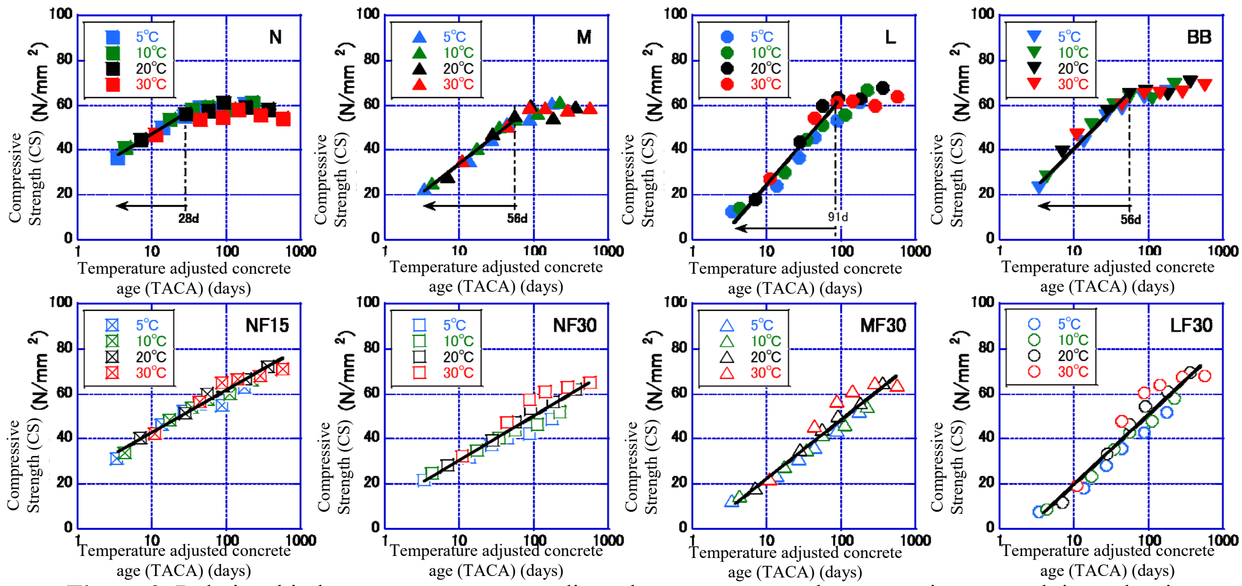

Figure 2. Relationship between temperature adjusted concrete age and compressive strength in each mix.

Table 6. Results of regression analysis for temperature adjusted concrete age and compression strength.

Symbol	Regression coefficient		Correlation coefficient	Regression interval
	a	b	R	
N	20.1	27.4	0.989	Up to Temperature Adjusted Concrete Age (TACA) 28 days
M	26.9	7.2	0.994	Up to TACA 56 days
L	36.3	-10.9	0.972	Up to TACA 91 days
BB	31.9	9.5	0.983	Up to TACA 56 days
NF15	18.1	24.8	0.976	Up to TACA 364 days
NF30	19.5	11.2	0.952	Up to TACA 364 days
MF30	26.1	-3.1	0.971	Up to TACA 364 days
LF30	31.5	-12.5	0.967	Up to TACA 364 days

Table 7. Results of regression analysis for temperature adjusted concrete age and static Young's modulus.

Symbol	Regression coefficient		Correlation coefficient	Regression interval
	a	b	R	
N	5.61	35.1	0.964	up to Temperature Adjusted Concrete Age (TACA) 28 days
M	6.70	29.9	0.990	up to TACA 56 days
L	9.69	24.9	0.976	up to TACA 91 days
BB	7.34	32.0	0.972	up to TACA 56 days
NF15	4.02	36.0	0.964	up to TACA 364 days
NF30	4.61	31.0	0.971	up to TACA 364 days
MF30	6.60	26.4	0.974	up to TACA 364 days
LF30	8.66	22.8	0.951	up to TACA 364 days

Table-6 shows the list of calculation results of regression coefficients “a” and “b”. The larger the regression coefficient “a”, the faster the increase in long-term strength, and the regression coefficient “b” represents the initial strength. The regression coefficients “a” for the mixes using FA respectively are close to those of Portland cement as the base material (87～97% to each cement). As is the case with the ranking of “a” of base cement (L> M> N), the ranking of the mix proportions using FA was in the order of LF30> MF30> NF30> NF15, and the regression coefficient “a” for BB was between that of M and L.

On the other hand, it was found from the ranking of regression coefficients “b” that the initial strengths of mix proportions are ranked in the order of N> NF15> NF30> BB> M> MF30> L> LF30. The initial strength of the mix proportion using FA decreases as the initial strength of the base cement decreases and as the FA replacement rate increases.

3.4 Relationship Between Temperature Adjusted Concrete Age and Static Young’s Modulus

Figure 3 shows the relationship between temperature adjusted concrete age and static Young’s modulus, and Table 7 shows the results of linear regression analysis. The range of regression analysis was the same as that of the compression strength regression analysis in Section 3.3.

The static Young’s modulus tended to develop in the same manner as the compressive strength. In other words, in the concretes without FA, the regression coefficient “a” was ranked in the order of L> BB> M> N, and in the concretes using FA, in the order of LF30> MF30> NF30> NF15. However, it was smaller than the regression coefficient “a” of compressive strength, generally with a small difference resulting from the temperature adjusted concrete age. On the other hand, the regression coefficient developed in the order of N> NF15> BB> NF30> M> MF30> L> LF30, and had an almost same tendency as the compressive strength, except for the fact that BB was slightly larger than NF30.

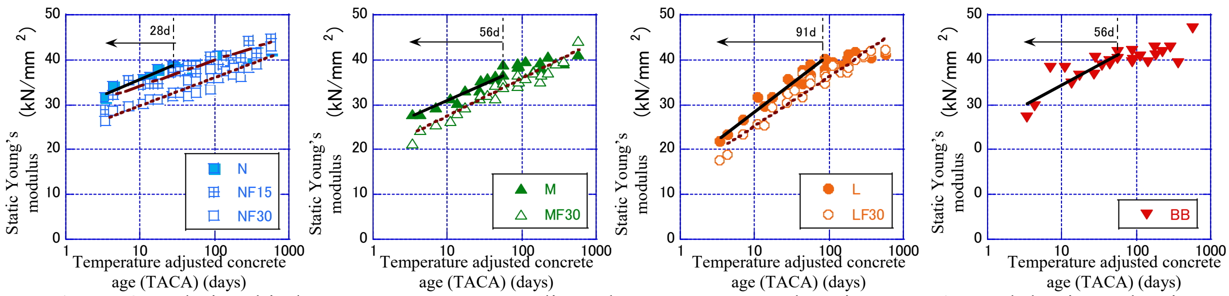

Figure 3. Relationship between temperature adjusted concrete age and static Young’s modulus in each mix

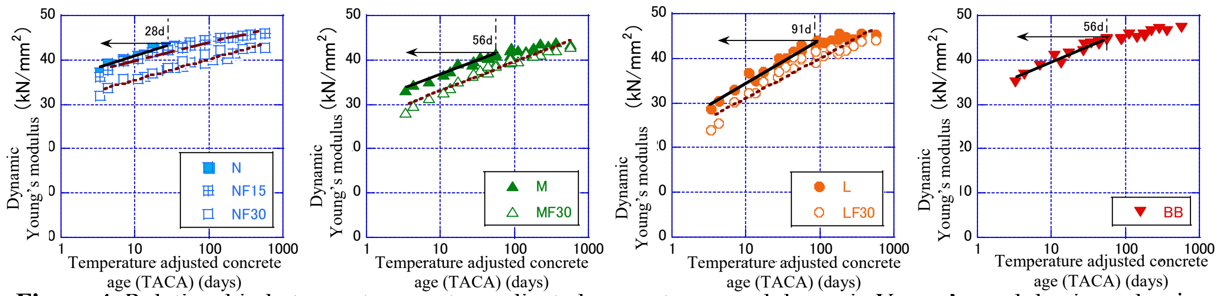

Figure 4. Relationship between temperature adjusted concrete age and dynamic Young’s modulus in each mix.

3.5 Relationship Between Temperature Adjusted Concrete Age and Dynamic Young's Modulus

Figure 4 shows the relationship between temperature adjusted concrete age and dynamic Young's modulus, and Table 8 the results of linear regression analysis. The range of regression analysis was the same as in Section 3.3.

From the difference in regression coefficient of "a", it was confirmed that the dynamic Young's modulus developed earlier than the compressive strength and static Young's modulus and tended to level off earlier with the age. The magnitude relationship of the regression coefficients "a" and "b" demonstrated the same tendency as in the static Young's modulus.

3.6 Relationship Between Compressive Strength and Young's Modulus

Figure 5 shows the relationship between compressive strength and static Young's modulus, Figure 6 shows the relationship between compressive strength and dynamic Young's modulus, and Figure 7 shows the relationship between static Young's modulus and dynamic Young's modulus.

Regardless of the types of binder or the use of FA, the relationship between compressive strength and static Young's modulus and the relationship between compressive strength and dynamic Young's modulus were constant. Moreover, the dynamic Young's modulus tended to fluctuate less than the static modulus.

The dynamic Young's modulus is generally given by the specimen's flexural vibration at which the specimen underwent resonant vibration. Since this modulus represents a status where almost no load works, it tends to grow larger than the static Young's modulus. (Ohmsha, 2004) In this experiment, as shown in Figure 7, the dynamic Young's modulus was larger than the static Young's modulus. This trend was more noticeable at young ages.

Table 8. Results of regression analysis for temperature adjusted concrete age and dynamic Young's modulus.

Symbol	Regression coefficient		Correlation coefficient R	Regression interval
	a	b		
N	5.61	35.1	0.964	up to Temperature Adjusted Concrete Age (TACA) 28 days
M	6.70	29.9	0.990	up to TACA 56 days
L	9.69	24.9	0.976	up to TACA 91 days
BB	7.34	32.0	0.972	up to TACA 56 days
NF15	4.02	36.0	0.964	up to TACA 364 days
NF30	4.61	31.0	0.971	up to TACA 364 days
MF30	6.60	26.4	0.974	up to TACA 364 days
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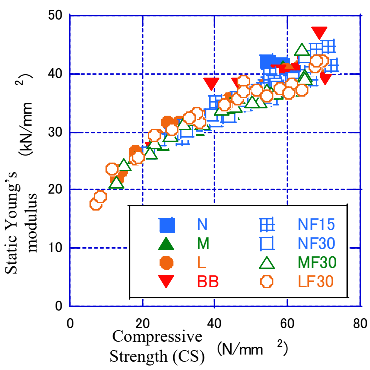

Figure 5. Relationship between compressive strength and static Young's modulus.

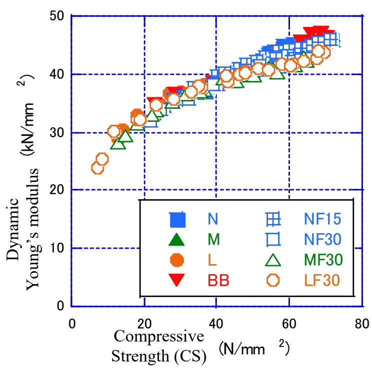

Figure 6. Relationship between compressive strength and dynamic Young's modulus.

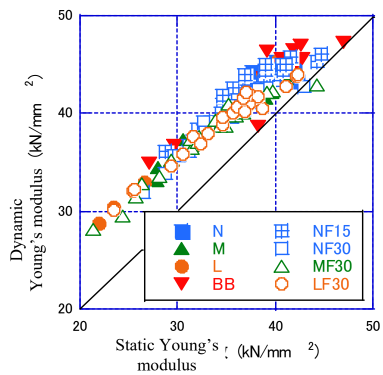

Figure 7. Relationship between static Young's modulus and dynamic Young's modulus.

4 Conclusion

The following two types of concrete, one using three Portland cements (N, M, L) with no FA and the other using the same cements but partially replaced by FA, at a water-binder ratio of 45% and cured at different curing temperatures, were comparatively studied in terms of the compressive strength up to one year of age as well as of static and dynamic Young's moduli, including an experiment using blast furnace cement B (BB). We compared the data of these specimens to determine their relationship with temperature adjusted concrete age. The obtained results obtained are as follows:

(1) The mix proportion with 30% of cement replaced by FA, despite increasing AE agent, recorded more than 0.5% decrease in air content which is presumably due to the effect of FA's unburned carbon.

(2) In the mix proportions (blending) of N, M, L and BB, the higher the temperature, the faster the strength developed. However, strength increase slowed down early and reached a peak. On the other hand, the mix proportions (blending) using FA steadily developed long-term strength regardless of the difference in binder and curing temperature, exceeding the long-term strengths of N and M. Especially N15, which is a mix proportion of N with 15% FA replacement, did not peak even at about 80 N/mm^2 of compressive strength which is 1.3 times N's peak of 60 N/mm^2, and we learned that FA substitution has a high impact on the compressive strength.

(3) In the mix proportions (blending) using N, M, L, and BB, it was shown that the strength increased highly correlated with the temperature adjusted concrete age (in logarithm) up to the moment its growth rate in strength slowed down. On the other hand, the mix proportions (blending) using FA developed the strength for a long span of time, keeping a close correlation with the temperature adjusted concrete age.

(4) It was found that for the mix proportions (blending) using FA, the lower the initial strength of the base cement or the higher the replacement rate of FA, the slower the strength development and that they demonstrate the characteristics of strength development which correspond to those of the base cement. The mix proportion (blending) using the binder with a slower initial strength development tended to result in the larger strength.

(5) Regardless of the use of FA in the mix, the relationship between compressive strength and static Young's modulus and the relationship between compressive strength and dynamic Young's modulus were constant. The dynamic Young's modulus demonstrated a larger value than the static Young's modulus, and this trend was more conspicuous at young ages.

ORCID

Takafumi Noguchi: https://orcid.org/0000-0001-6115-2292

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