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Original research article

Early-Age Compressive Strength of No-Slump Concrete Taking into Account the Effect of Curing Temperature

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ABSTRACT

This paper presents the results of a study carried out to investigate early-age compressive strength of no-slump concrete (including pre-cast concrete and roller-compacted concrete) in the presence of fly ash and the effect of curing temperature. In this study, the used binders include ordinary Portland cement type I and fly ash. The replacement ratios of fly ash were varied from 0%, 15% and 30% by weight of total binder. In order to evaluate the effect of curing temperature on compressive strength, laboratory specimens were cured at isothermal conditions of 30°C (considered as an average normal temperature in Thailand), 45°C and 70°C. Compressive strength results were collected at 6 hours, 12 hours, 1 day, 3 days, 7 days and 28 days. The results of the study reveal that although the presence of fly ash increases consistency of fresh concrete significantly, it delays compressive strength development at early ages. However, at elevated curing temperature, it significantly affects compressive strength development at early ages. Furthermore, there exists an appropriate curing temperature to gain optimal strength at specific ages of concrete. This temperature depends on factors such as water to binder ratio, replacement ratio of fly ash in the binder, etc.

Keywords: Curing temperature; Early-age compressive strength; Fly ash; No-slump concrete

1. Introduction

Besides conventional concrete, a special type of concrete popularly used in civil engineering construction is no-slump concrete. No-slump concrete is known as concrete which has zero slump due to its

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very dry mixture. No-slump concrete is normally applied in two typical types of concrete i.e. roller compacted concrete (RCC) and pre-cast concrete.

RCC is often applied for construction of dams, mat foundations, pavements and industry floors, while pre-cast concrete is often fabricated in the factory or on site in the forms of components of buildings, components of bridges, some types of blocks and liquid pipes, etc. The main benefits of no-slump concrete in RCC and pre-cast concrete are its rapid construction and high durability of the concrete products. This leads to lower cost of construction and enhanced quality of the concrete.

In the fabricating process of RCC, especially RCC for dams, a large amount of fly ash is often used as a material replacing part of the cement to obtain lower cost and to improve some properties of the concrete. Additionally, fly ash is used for other types of RCC such as RCC for pavements. The use of fly ash is not only to salvage industry wastes and solve environmental problems, but also to improve some concrete properties such as reducing water demand, reducing heat generation, increasing abrasion resistance, enhancing workability, reducing permeability and chloride ion penetration, improving resistance to sulfate attack, reducing alkali-aggregate reaction and reducing drying shrinkage [1].

However, in practice, the use of fly ash in concrete still involves a number of limitations [2-3]. This is caused by the variance in physical properties and chemical compositions due to the change of type of coal and the process of coal burning. Due to this reason, selecting the proper mix proportion (for satisfactory durability and low cost) requires a number of trial mixings to account for the change of fly ash properties affecting the properties of fresh and hardened concrete. This consumes time and increases expense. In addition, the change of ambient temperature is a factor strongly affecting strength development of concrete, especially at the early ages. Hence, considering the effect of curing temperature in design mix proportion of concrete is necessary. It is, in many situations, beneficial for pre-cast concrete to be cured at elevated temperature to accelerate mechanical strength development. The more precise estimation of actual strength of roller-compacted concrete in dams also provides benefits for design and behavior analysis of the dam.

In addition, in the manufacturing process of no-slump concrete, consistency and early-age compressive strength are generally two important factors that need to be considered because they affect not only properties of the concrete, but also cost of the concrete products. Thus, the study of the relationship between those two factors is necessary. This will support civil engineers in designing the mixture proportion of no-slump concrete and improve the manufacturing process of no-slump concrete.

For these reasons, it is necessary to conduct studies on strength development of no-slump concrete using fly ash at early-age state taking into account the effect of curing temperature.

2. Experimental Program

2.1 Materials

Physical properties of OPC type I, fly ash, fine aggregates and coarse aggregates are shown in Table 1, whereas chemical compositions of OPC type I and fly ash are tabulated in Table 2. The scanning electron microscope (SEM) pictures of OPC type I and fly ash are illustrated in Fig. 1 and Fig. 2 shows gradation of fine and coarse aggregate.

Table 1. Physical properties of OPC type I, fly ash, fine aggregate and coarse aggregate.

Physical properties	OPC Type I	Fly ash	Sand	Gravel
Specific gravity	3.15	2.10	2.62	2.70
Blaine fineness (cm^2/g)	3150	2910	-	-
Fineness modulus	-	-	2.83	7.34
Maximum size (mm)	-	-	4.75	19

Table 2. Chemical compositions of OPC type I and fly ash.

Chemical Compositions (%)	OPC Type I	Fly ash
SiO_2	20.61	43.12
Al_2O_3	5.03	22.04
Fe_2O_3	3.03	9.78
CaO	64.89	12.55
MgO	1.43	3.09
Na_2O	0.22	1.30
K_2O	0.46	5.22
SO_3	2.70	2.76
Loss on ignition	1.23	0.00
Free Lime	0.79	-
Gymsum Content	5.6	-
Tricalcium Silicate (C_3S)	57	-
Dicalcium Silicate (C_2S)	17	-
Tricalcium Aluminate (C_3A)	8.3	-
Tetra Ca-Al-Ferrite (C_4AF)	10	-

2.2 Mix proportions

The parameters considered in this study consist of water to binder ratio (w/b), ratio of volume of paste to volume of void of aggregate (γ), replacement ratio of fly ash (R) and curing temperature (T). Details of mix proportions are provided in Table 3.

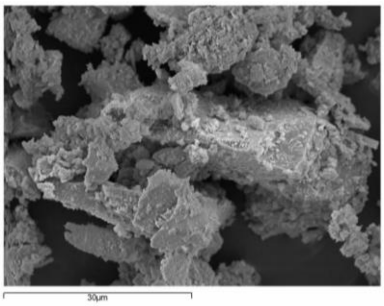
2.3 Test methods

(a) Consistency test: The procedure of the determination of consistency of fresh no-slump concrete was based on British Standard 1881: Part 104:1983 Testing concrete: Method for determination of Vebe time. Mixtures in Table 3 were tested by using Vebe test at three time steps, i.e. at 0 minutes, 30 minutes and 60 minutes after mixing.

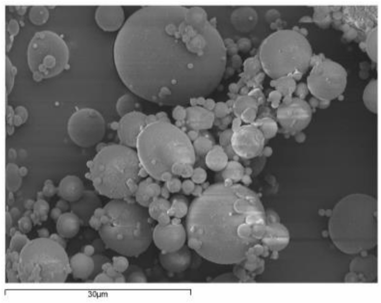
Table 3. Mix proportions of no-slump concrete.

Mix No.	γ	w/b	R (%)	Cement (kg)	Fly Ash (kg)	Water (l)	Sand (kg)	Gravel (kg)
M1	1.05	0.3	0	380	0	114	856	1158
M2	1.05	0.3	15	311	55	110	856	1158
M3	1.05	0.3	30	247	106	106	856	1158
M4	1.20	0.3	0	437	0	131	816	1104
M5	1.20	0.3	15	357	63	126	816	1104
M6	1.20	0.3	30	284	122	122	816	1104
M7	1.05	0.4	0	327	0	131	856	1158
M8	1.05	0.4	15	269	47	127	856	1158
M9	1.05	0.4	30	215	92	123	856	1158
M10	1.20	0.4	0	376	0	150	816	1104
M11	1.20	0.4	15	309	55	145	816	1104
M12	1.20	0.4	30	247	106	141	816	1104

(b) Compressive strength test: In order to avoid evaporation of water of specimens during the curing process, the specimens were covered by three layers of aluminum foil and three layers of plastic film after being demoulded, as shown in Fig. 3. Then, they were stored in a controlled temperature oven to start curing. Specimens were cast in ∅100x200 mm cylindrical steel moulds. Compressive strength results were collected at the ages of 6 hours, 12 hours, 1 day, 3 days, 7 days and 28 days.

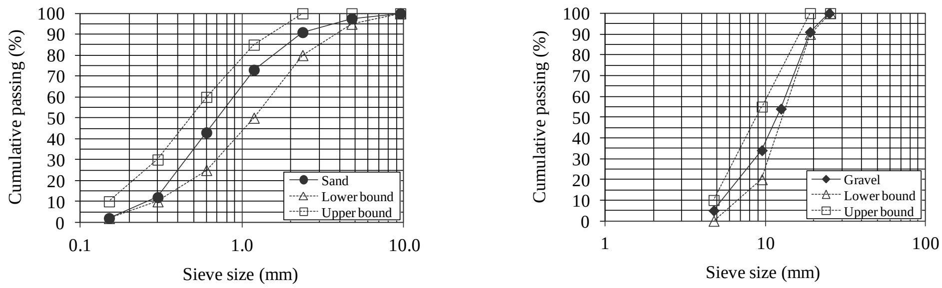


(a) OPC type I (zoom 2000x)



(b) fly ash (zoom 2000x)

Fig. 1. SEM pictures of OPC type I and fly ash.



(a) sand (b) gravel

Fig. 2. Gradation of aggregates.

Fig. 3. Specimen covered by foil and plastic sheet.

3. Results and Discussion

3.1 Consistency

Table 4 presents the results of consistency of mixtures at 0, 30 and 60 minutes after mixing. According to these results, as in the case of workability of normal concrete with fly ash, consistency of no-slump concrete is proportional to water to binder ratio, ratio of paste to void of aggregate and fly ash ratio in binder [4]. Vebe time of no-slump concrete reduces as value of w/b and replacement ratio of fly ash and paste to void of aggregate increases.

3.2 Compressive strength

3.2.1 Influence of water to binder ratio (w/b) and ratio of paste to void of aggregate (γ) on strength development of no-slump concrete

The data in Tables 4 and 5 show that, similar to normal fly ash concrete [5], compressive strength of no-slump concrete decreases as w/b increases at all curing temperatures (30°C, 45°C, 70°C). The w/b directly affects microstructure formation by affecting the mean inter-particle distance and volume of capillary voids. Hence, lower w/b can reduce porosity in the paste matrix and leads to a denser structure of paste, as a result increasing compressive strength of the concrete.

Similarly, the effect of γ on compressive strength of no-slump concrete can be found from Tables 4 and 5. It can be seen that, at the same w/b and replacement ratio of fly ash, the change of γ from 1.05 to 1.2 only slightly affects compressive strength (see an example in Fig. 4). This is because γ value of zero-slump concrete is lower than that of normal concrete and the change of this value is within a narrow interval. Moreover, a large amount of aggregate with high density and high compaction energy are the factors strongly affecting compressive strength of no-slump concrete. However, based on experimental results, it can be inferred that the mixtures having value of γ equal 1.05 provide slightly better compressive strength than the mixtures with γ = 1.2.

Table 4. Experimental results of compressive strength, rate of compressive strength development (ϕ) and Vebe values at normal temperature (30±2°C).

Mix No.	Compressive strength (MPa) at 30°C						Strength development ratio (ϕ)						VB (seconds)		
	6 hours	12 hours	1 day	3 days	7 days	28 days	6 hours	12 hours	1 day	3 days	7 days	28 days	Minutes after mixing		
													0	30	60
M1	14.32	31.16	46.92	53.82	63.52	69.32	0.207	0.450	0.677	0.776	0.916	1.0	41	58	76
M2	8.10	23.22	38.91	52.45	58.18	65.34	0.124	0.355	0.596	0.803	0.891	1.0	34	42	56
M3	3.68	17.46	34.09	45.22	53.52	61.34	0.060	0.285	0.556	0.737	0.872	1.0	28	36	48
M4	14.12	32.65	48.05	54.49	62.43	68.32	0.207	0.478	0.703	0.798	0.914	1.0	24	34	47
M5	7.68	20.38	38.35	49.98	56.86	61.32	0.125	0.332	0.625	0.815	0.927	1.0	16	24	40
M6	3.26	16.71	29.90	45.24	49.94	56.73	0.057	0.294	0.527	0.797	0.880	1.0	15	21	34
M7	5.93	21.41	32.62	41.76	47.82	55.49	0.107	0.386	0.588	0.753	0.862	1.0	16	28	42
M8	3.73	15.91	24.18	33.71	39.82	48.57	0.077	0.328	0.498	0.694	0.820	1.0	10	16	28
M9	1.87	9.42	20.50	30.72	36.02	46.11	0.040	0.204	0.445	0.666	0.781	1.0	8	13	22
M10	4.67	20.66	33.82	45.37	51.35	59.62	0.078	0.347	0.567	0.761	0.861	1.0	9	14	22
M11	3.31	12.61	21.29	32.32	36.96	50.67	0.065	0.249	0.420	0.638	0.729	1.0	5	7	10
M12	1.86	8.79	17.08	25.77	32.04	45.80	0.041	0.192	0.373	0.563	0.700	1.0	4	5	8

Table 5. Experimental results of compressive strength at elevated curing temperature (45°C and 70°C).

Mix No.	Compressive strength (MPa) at 45°C						Compressive strength (MPa) at 70°C					
	6 hours	12 hours	1 day	3 days	7 days	28 days	6 hours	12 hours	1 day	3 days	7 days	28 days
M1	23.98	39.26	47.53	54.23	58.26	63.32	36.17	48.72	53.32	56.76	59.43	61.47
M2	18.58	34.57	43.36	52.42	57.78	62.65	23.76	37.29	42.96	51.13	56.91	60.31
M3	10.87	29.24	38.67	46.62	52.35	58.21	16.28	27.62	40.50	47.70	51.81	55.45
M4	25.93	42.38	51.62	56.81	60.92	63.88	32.93	43.73	49.79	53.52	57.96	60.10
M5	20.13	33.22	44.63	51.26	57.30	61.50	24.12	36.83	46.27	53.15	57.11	60.49
M6	7.57	26.63	37.34	46.87	53.16	57.41	16.91	28.73	42.17	49.38	55.73	58.22
M7	16.39	29.05	40.63	46.56	49.47	53.88	19.42	28.22	33.68	39.20	43.02	46.68
M8	9.82	22.35	31.44	38.10	43.20	50.30	14.13	21.05	28.10	34.15	37.50	43.49
M9	6.86	18.08	27.10	36.36	41.52	47.21	11.41	16.94	26.16	33.48	36.92	39.58
M10	14.57	28.10	36.36	42.47	48.10	54.14	20.42	27.36	34.45	38.62	40.85	43.32
M11	8.49	18.43	26.12	34.32	40.24	46.27	13.32	20.67	30.54	36.97	38.82	42.11
M12	4.90	13.09	22.73	28.22	35.02	43.94	9.90	17.06	27.54	33.28	35.21	38.56

3.2.2 Influence of fly ash on strength development of no-slump concrete at normal temperature (30±2°C)

Table 4 contains data of compressive strength and strength development ratio (denoted by ϕ) at normal curing temperature of 30°C. The strength development ratio at a certain age is defined as the ratio of compressive strength at that age to its compressive strength at the age of 28 days. The results show that, like normal fly ash concrete, the presence of fly ash in no-slump concrete appears to significantly reduce early-age compressive strength.

The rate of the reduction depends upon the replacement ratio of fly ash and curing temperature. The mixtures with high fly ash to binder ratio provide lower compressive strength at early age than the mixtures with lower fly ash to binder ratios. This can be seen in Fig. 5. The reduction of the compressive strength due to the presence of fly ash up to 28 days in this study is clear. However, it can also be seen from Table 4 that the rate of compressive strength development of mixtures with the presence of fly ash at later ages seems to gradually increase.

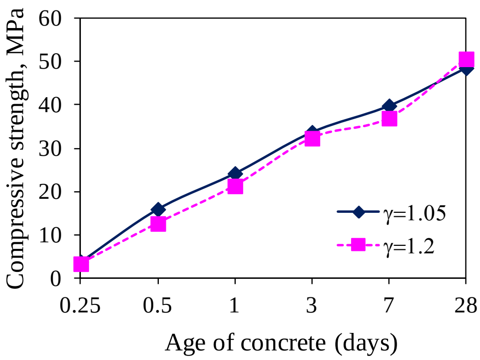


Fig. 4. Comparison of compressive strength development of no-slump concrete cured at 30±2°C, w/b=0.4, R=15%.

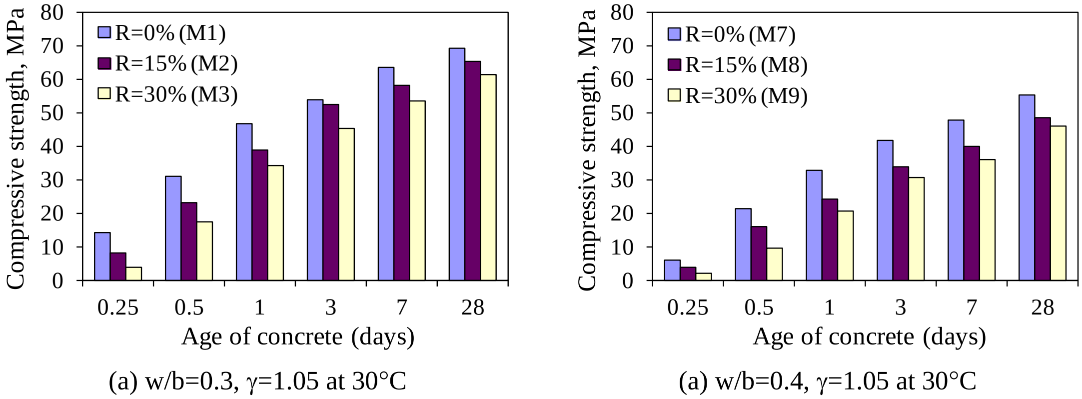


Fig. 5. Comparison of compressive strength development of no-slump concrete cured at normal temperature.

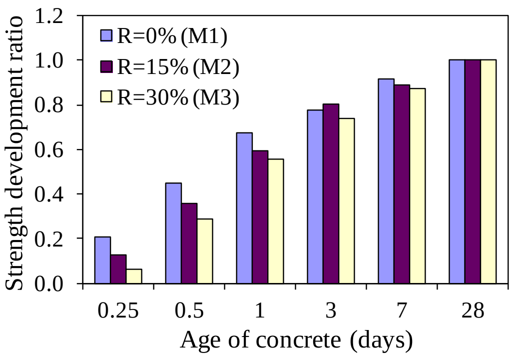
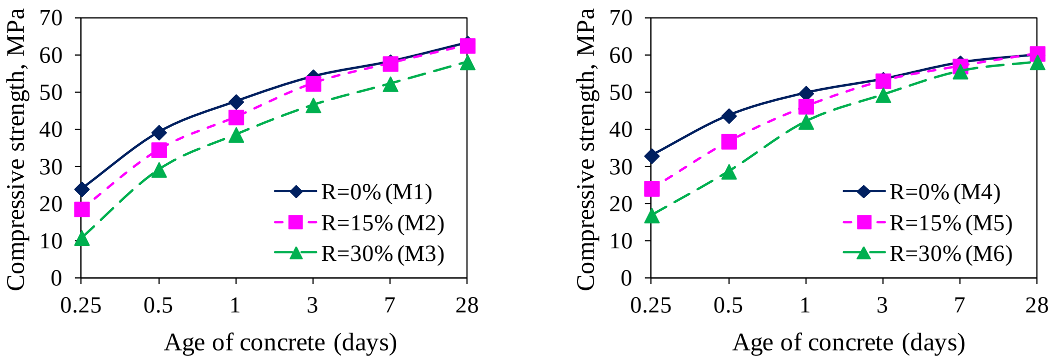


Fig. 6. Comparison of compressive strength development ratio (ϕ) of no-slump concrete cured at normal temperature and w/b=0.3, γ=1.05.

The ϕ values of mixtures with fly ash at later ages become closer to the ϕ values of mixtures with cement only as illustrated in Fig. 6. This can be explained as pozzolanic reaction not occurring at early ages or reactivity is very weak resulting in low strength development ratio. However, ϕ values significantly improve at later ages when reactivity becomes higher. This period depends on the type of fly ash [1, 6]. The period may be a week or longer in the case of fly ash class F [1]. In the case of fly ash class C, the period is shorter [6]. This can be explained by the fact that lime content in fly ash class C is higher than that of fly ash class F and crystalline C_2S and C_3A may also be present in fly ash class C. This rapidly increases pH value inside pore water of the concrete due to $Ca(OH)_2$ generated from the hydration. After a certain period of hydration process, when pH value in pore water solution reaches the necessary value, the pozzolanic reaction of fly ash starts occurring.

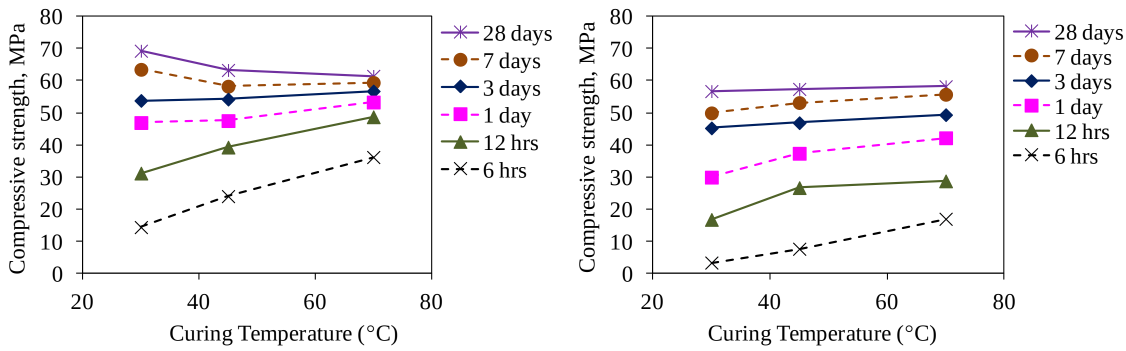
3.2.3 Influence of curing temperature on strength development of no-slump concrete

Similar to the case of normal temperature curing, when cured at elevated temperature, mixtures with the presence of fly ash have lower compressive strength than that of mixtures with cement only at early-age state.



(a) w/b=0.3, γ=1.05 at 45°C (b) w/b=0.3, γ=1.2 at 70°C

Fig. 7. Comparison of compressive strength development of no-slump concrete cured at elevated curing temperature.



(a) w/b=0.3, γ=1.05, R=0% (b) w/b=0.3, γ=1.2, R=30%

Fig. 8. Relationship between curing temperature and compressive strength of no-slump concrete.

However, at the later ages, some mixtures provided comparable compressive strength to that of mixtures with cement only. This can be seen in Figs. 7a and 7b which show that mixture M2 with 15 % fly ash has almost equal compressive strength to mixture M1 with cement only (Fig. 7a). Mixtures M5, M6 also show comparable strength at 28 days to the mixture M4 in Fig. 7b.

From Table 5, it can be seen that evaluated curing temperature is of benefit for compressive strength at early ages (up to 7 days) for all mixtures. However, for the mixtures with cement only, curing at high temperature reduces compressive strength at later ages as illustrated in Fig. 8a. This is however different from mixtures with fly ash in which high curing temperature also improves strength development at later ages as illustrated in Fig. 8b. So, this result confirms a conclusion for no-slump concrete like previous conclusions of normal concrete by many authors that elevated curing temperature accelerates compressive strength development at early ages, but reduces ultimate compressive strength of concrete with cement only [1, 5].

In the case of fly ash concrete, according to Fraay et al. [7], elevated curing temperature induces a hydration process of cement, leading to a rapid increase of OH^- ion concentration in pore water of concrete. Early in the process the pH value reaches the necessary value for pozzolanic reaction to take place. In addition, Malhotra [8] indicated that if the pozzolanic reaction has started, this process will carry on even if the curing temperature is reduced. It appears that once the surfaces of fly ash particles have been dissolved, the reaction can occur more easily.

This effect of elevated curing temperature is particularly beneficial for pre-cast concrete which is cured by high temperature curing methods, such as steam curing method, to accelerate strength development of their products.

According to the results in Tables 5 and 6, depending upon each mixture (with specific value of w/b, γ and R%), there exists an optimal curing temperature to gain beneficial ultimate compressive strength as illustrated in Figs. 6a and 6b. In this study, 12 mixtures were undertaken, in the range of curing temperature 30°C up to 70°C. Based on the graphs in Figs. 6a and 6b, the appropriate curing temperature can be found for each mixture at certain age of concrete (6 hours to 28 days) to gain satisfactory strength at desired ages with reasonable energy spent for the curing process. This is particularly beneficial for pre-cast concrete which uses a controlled curing process to accelerate strength development. These test results are also useful for the establishment of a model for predicting compressive strength of no-slump fly ash concrete cured under various temperature conditions [9].

4. Conclusions

Based on the above discussions, some conclusions can be drawn as follows:

1. Consistency of no-slump concrete is proportional to w/b and replacement of fly ash in binder and ratio of paste to void of aggregate.

2. Compressive strength is affected by w/b, replacement ratio of fly ash. However, the change of γ of no-slump concrete in the tests, ranging from 1.05 to 1.2, insignificantly affects compressive strength at normal curing temperature as well as at elevated curing temperature.

3. With the same volume of binder, the presence of fly ash in no-slump concrete reduces compressive strength at early ages (up to 28 days) significantly. However, at later ages, the rate of compressive strength development of mixtures with fly ash is higher than mixtures with cement only.

4. Elevated curing temperature accelerates compressive strength development of no-slump concrete at early ages but reduces ultimate compressive strength of no-slump concrete with cement only.

Acknowledgements

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