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Mechanical properties and adiabatic temperature rise of low heat concrete using ternary blended cement

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Abstract. This study examined the mechanical properties and adiabatic temperature rise of low-heat concrete developed based on ternary blended cement using ASTM type IV (LHC) cement, ground fly ash (GFA) and limestone powder (LSP). To enhance reactivity of fly ash, especially at an early age, the grassy membrane was scratched through the additional vibrator milling process. The targeted 28-day strength of concrete was selected to be 42 MPa for application to high-strength mass concrete including nuclear plant structures. The concrete mixes prepared were cured under the isothermal conditions of 5°C, 20°C, and 40°C. Most concrete specimens gained a relatively high strength exceeding 10 MPa at an early age, achieving the targeted 28-day strength. All concrete specimens had higher moduli of elasticity and rupture than the predictions using ACI 318-11 equations, regardless of the curing temperature. The peak temperature rise and the ascending rate of the adiabatic temperature curve measured from the prepared concrete mixes were lower by 12% and 32%, respectively, in average than those of the control specimen made using 80% ordinary Portland cement and 20% conventional fly ash.

Keywords: mass concrete; ternary blended concrete; mechanical properties; adiabatic temperature rise

1. Introduction

Recently, as concrete structures are becoming larger and higher strength, the use of mass concrete has been increasing; accordingly, more attention is being given to the control of concrete hydration. Hydration heat rises in mass concrete affect the occurrence of cracks, which degrades the stability, durability, and waterproofing property performance of structures, thereby resulting in a fundamental shortening of the structure's lifetime (Alhozaimy *et al*. 2015). Typically, in construction applications, the methods used to reduce hydration heat of mass concrete are precooling methods that cool down the mixing water or aggregate used and post cooling methods that make cooling water pass through pipes installed in concrete members (Kim *et al*. 2001).

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With regard to materials, studies on low heat concrete for reducing the heating value of the concrete have been continuously conducted (Zhu *et al*. 2014).

Generally, in low heat concrete, moderate heat Portland cement and low heat Portland cement are used to reduce hydration heat, and fly ash (FA) is used as an admixture in place of cement to reduce hydration heat, enhance long-term strength, and improve workability (Atis 2002 and Mala *et al*. 2013). Various studies have been conducted lately to explore this method, including OPC and fly ash (binary blended cement) or OPC, fly ash, and slag powder (ternary blended cement) (Vance *et al.* 2013, Kumar *et al.* 2013 and De Weerdt *et al.* 2011). However, when a large amount of cement is replaced by FA, the development of initial strength is delayed by pozzolanic reaction (Shon *et al.* 2003, and Morarrah and Husasin 2013). In particular, such a delay can extend the form removal time, which could be a major cause of construction cost increases due to the extension of the entire construction period; in winter, freezing damage could result from insufficient curing (Zhu *et al*. 2014 and Shaikh *et al*. 2015). Particles of fly ash are globular shaped and glassy films form on their surfaces. If the fineness of the particles is enhanced through physical grinding, the glassy films are removed and initial Pozzolanic reactions are activated so that the activity factor of the hydration reaction is improved; such a process is effective for intensifying the compressive strength (Ramezanianpour *et al.* 2009, Shaikh *et al.* 2015 and Kocak and Nas 2014). In addition, as a way to enhance concrete strength, there is a method in which limestone powder (LSP) is used as an admixture to fill the micropores in the concrete (filler effect) (Bentz 2005, Bentz *et al.* 2009, Kwan *et al.* 2014, Meddah *et al.* 2014 and Weerdt *et al.* 2011). ASTM Standard (C150-04) recommends a replacement ratio of 5% of the amount of binders when LSP is used (Ramezanianpour *et al.* 2009).

In the present study, for hydration heat reduction and early strength enhancement, we used low heat Portland cement (LHC), fine-ground FA (GFA), and LSP. Considering seasonal curing environments, compressive strength, bending strength, and tensile strength tests, as well as adiabatic temperature rise, tests were conducted in cold weather (5°C), standard weather (20°C), and hot weather (40°C) conditions to assess the mechanical characteristics and adiabatic temperature rises of the various materials to validate their applicability as mass concrete.

2. Experimental detail

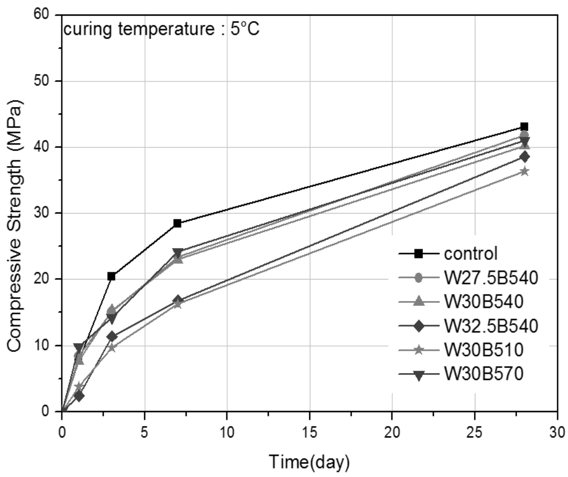
To assess the mechanical characteristics of concrete and the design criterion strength of the concrete specimens applied with LHC, GFA and LSP was set at 41.3 MPa (6,000 psi); the major variables of the mix design included the unit binder contents and water to binder ratios (*W/B*). The experimental mix design is shown in Table 1.

In mass concrete, considering hydration heat reduction and compressive strength, FA is generally used in place of 20% of the cement. Therefore, ordinary Portland cement (OPC) 80% and FA 20% were determined as binders for the control mix (ACI 318). In the present study, for hydration heat reduction and early compressive strength enhancement, LHC 80%, GFA 15%, and LSP 5% were used as binders for the experimental mix. The fineness of LHC (ASTM Type IV) is approximately 3,000 cm^2/g and it is effective for hydration heat reduction and long-term strength development because its belite (C_2S) content is high. The fineness values of the FA and GFA used in the present study were 3,520 cm^2/g and 4,500 cm^2/g, respectively, and the fineness of the LSP was 3,420 cm^2/g. The *W/B* and unit binder contents, which are mix variables, were set to 27.5%, 30%, and 32.5% and 510, 540, and 570 kg/m^3, respectively, considering the design compressive

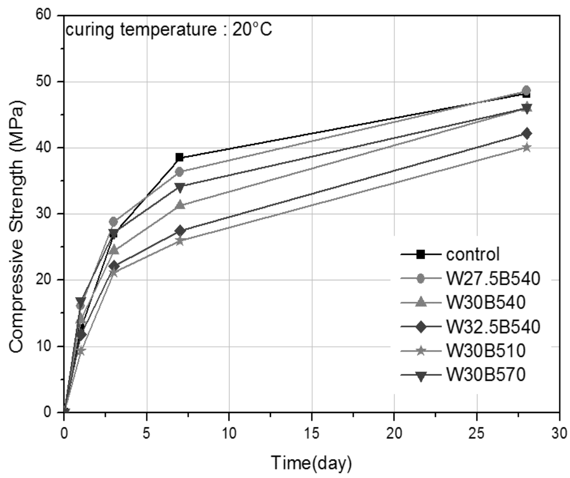
Table 1 Concrete mixture proportions

Specimens	*W/B* (%)	S/a (%)	B (kg/m^3)	OPC (%)	LHC (%)	FA (%)	GFA (%)	LSP (%)	SP (%)
Control	35		460	80	-	20	-	-	0.7
W27.5B540	27.5		540	-		-			1.6
W30B540	30	45	540	-		-			1.4
W32.5B540	32.5		540	-	80	-	15	5	1.2
W30B510	30		510	-		-			1.4
W30B570	30		570	-		-			1.4

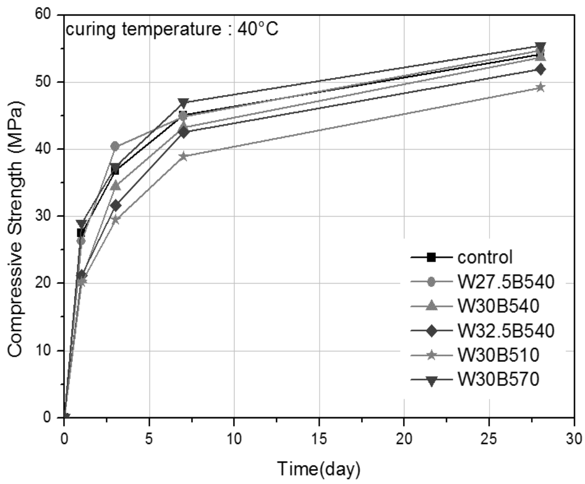
W/B : water-to-binder ratio (W), S/a : sand/aggregate ratio, B: unit binder content,
OPC : Ordinary Portland cement (ASTM Type I), LHC : Low Heat Portland Cement (ASTM Type IV),
FA : Fly Ash, GFA: Fine-Ground Fly Ash, LSP : Limestone Powder, SP : Super Plasticizer



(a) Curing temperature of 5°C



(b) Curing temperature of 20°C



(c) Curing temperature of 40°C

Fig. 1 Compressive strength development up to an age of 28 days

Table 2 Test results including slump, air content and compressive strength development

Specimens	Curing temperature (°C)	Slump (mm)	Air content (%)	Compressive strength (MPa)			
				1 day	3 days	7 days	28 days
Control	5	150	4.7	7.8	20.5	28.5	43.1
	20			12.7	27.0	38.5	48.2
	40			27.5	36.8	45.1	54.2
W27.5B540	5	138	4.2	8.4	15.1	23.4	41.8
	20			16.1	28.8	36.4	48.6
	40			26.3	40.4	44.9	54.7
W30B540	5	142	4.7	7.7	15.3	23	40.2
	20			14.1	24.5	31.3	46.1
	40			20.7	34.5	43.3	53.7
W32.5B540	5	140	3.9	2.4	11.4	16.8	38.6
	20			11.8	22.1	27.5	42.2
	40			21.2	31.6	42.6	52
W30B510	5	135	4.1	3.8	9.7	16.3	36.4
	20			9.3	21.2	26	40.1
	40			20.2	29.5	38.9	49.2
W30B570	5	146	3.9	9.8	14.2	24.2	41
	20			16.9	27.2	34.2	46.1
	40			29	37.4	47	55.4

strength. For all mixes, the S/a was fixed at 45% and polycarbonate-based, high-performance water-reducing admixtures were used. To assess the mechanical characteristics of the concrete in relation to the curing environment, all mixes were cured at 5°C, 20°C, and 40°C. The items measured were compressive strength by material age (1, 3, 7, and 28 days), and the modulus of rupture and tensile strength at a material age of 28 days, stress-strain relationships, and Young's modulus were analyzed.

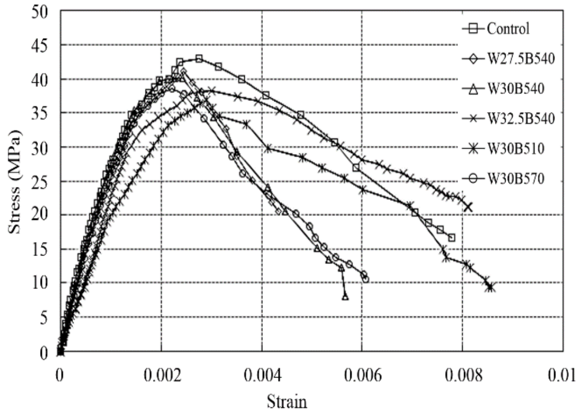
3. Test results and discussion

3.1 Fresh concrete

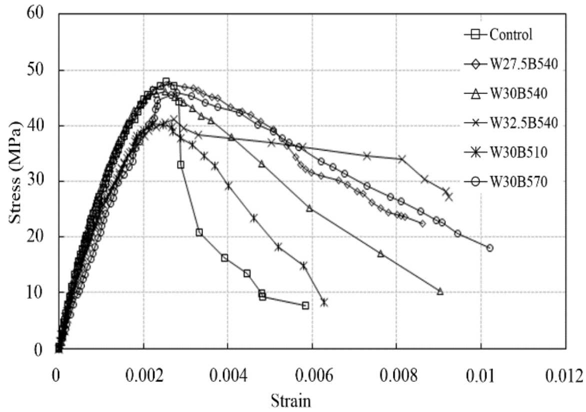
The measurement results for the individual mixes are shown in Table 2. The targeted slump was 150 mm and the admixture amounts were adjusted to secure fluidity. According to the experimental results, the range of slumps for the individual mix variables was 135~150 mm. The targeted air content was 4.5% and the range of air contents for all mixes was 3.9~4.7%.

3.2 Compressive strength in relation to curing temperatures

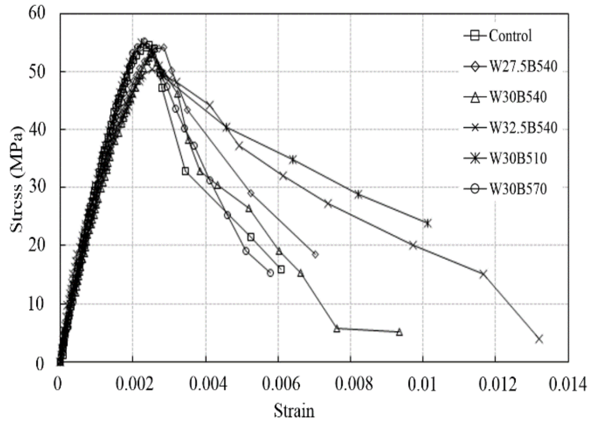
As a characteristic of the compressive strength development of all specimens, as shown in



(a) Curing temperature of 5°C



(b) Curing temperature of 20°C



(c) Curing temperature of 40°C

Fig. 2 Stress-strain curves of different concrete mixtures

Table 2, compressive strength tended to increase as the *W/B* decreased and the unit binder contents increased. According to the results of experiments on compressive strength in relation to curing temperatures, the mixes that satisfied the designed base strength at 41.3M Pa at the material age of 28 days were W27.5B540 and W30B570 at 5°C, the W30B540 mix at 20°C, and the W32.5B540 mix at 40°C. The effects of the major variables on compressive strength were larger at early material ages, and compressive strength development rates were shown to be higher at higher curing temperatures. Based on the compressive strength of material aged 28 days, the compressive strength development rates at lower material ages (1, 3, and 7 days) were approximately 6~26% (1 day), 27~38% (3 days), 43~64% (7 days) at the curing temperature of 5°C, 23~37% (1 day), 52~59% (3 days), and 64~80% (7 days) at the curing temperature of 20°C, and 38~52% (1 day), 60~74% (3 days), 79~85% (7 days) at the curing temperature of 40°C. In the low temperature curing environment (5°C) with low early compressive strength development rates, on the basis of W30B540, when the *W/B* increased by 2.5% (W32.5B540) or the binder content decreased by 3.7% (W30B510), the compressive strength decreased by approximately 40% compared to W30B540. In structures for which durability is important, form removal time requires 10 MPa or

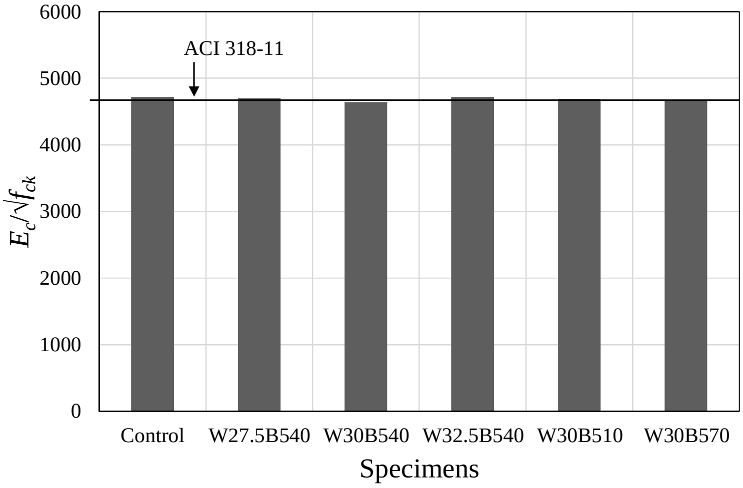


Fig. 3 $\boldsymbol{E_c}/\sqrt{f_{ck}}$ of ternary blended concrete

higher of concrete compressive strength. As shown in Fig. 1, in 20°C and 40°C curing environments, all mixes except for the W30B510 specimens showed compressive strengths of 10 MPa or higher, and in 5°C environments, all mixes except for the W30B510 specimens secured 10 MPa or higher compressive strength readings in 3 days. Therefore, the ternary blended low heat concrete presented in the present study is deemed to enable control of concrete compressive strength performance in cold weather and hot weather environments through the adjustment of the *W/B* and binder contents.

3.3 Stress-strain relationships and elastic coefficient

The stress-strain relationships of ternary blended concrete by temperature are shown in Fig. 2. At initial stiffness and maximum stress, strain increased as the *W/B* decreased, unit binder contents increased, and curing temperatures increased. In general, strain at the concrete's initial stiffness and maximum stress is shown to be higher when compressive strength is higher. The strain of the specimens at initial stiffness and maximum stress is also considered attributable to changes in the concrete's compressive strength resulting from changes in the *W/B*, unit binder contents, and curing temperatures. Meanwhile, the slopes of the ternary blended concretes in relation to initial stiffness were shown to be closer to each other at higher curing temperatures, regardless of changes in the *W/B* and unit binder contents, because the compressive strength levels of different mixes were formed in similar ranges when curing temperatures were high.

The results of the non-dimensionalization of the elastic coefficients (E_c) of the concretes cured at 20°C with 28 day compressive strength ($\sqrt{f_{ck}}$) for dimensional analysis are shown in Fig. 3. The $E_c/\sqrt{f_{ck}}$ values of the concretes were in the range of 4,641~4,719 and there were no effects on the *W/B* and unit binder contents. When compared to the predicted values of the elastic coefficients of ACI 318-11 ($E_c/\sqrt{f_{ck}} = 4{,}700$), the $E_c/\sqrt{f_{ck}}$ values of the concretes showed similar levels and those of W30B540, W30B510, and W30B570 were shown to be lower than the design criteria in ACI.

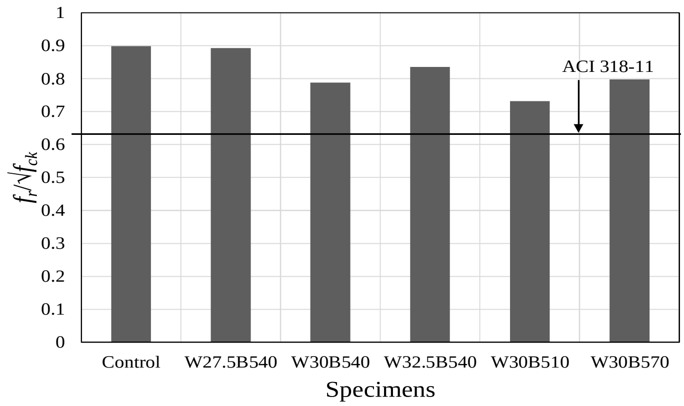


Fig. 4 $\boldsymbol{f_r/\sqrt{f_{ck}}}$ of ternary blended concrete

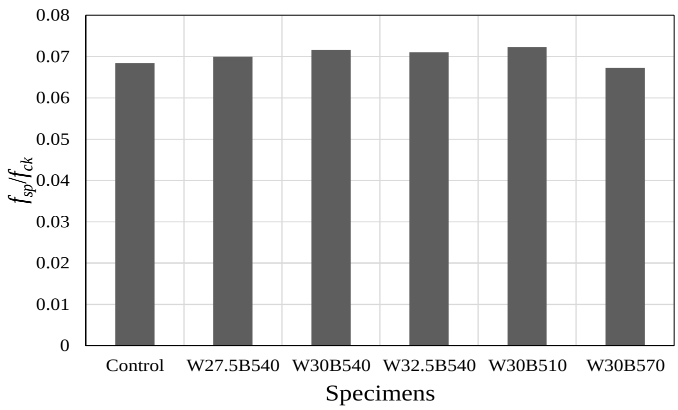


Fig. 5 $\boldsymbol{f_{sp}/f_{ck}}$ of ternary blended concrete

3.4 Coefficient of rupture and tensile strength (splitting tensile strength)

The results of the non-dimensionalization of the coefficients of rupture (f_r) of the ternary blended concretes cured at 20°C with 28 day compressive strength ($\sqrt{f_{ck}}$) for dimensional analysis are shown in Fig. 4. The $f_r/\sqrt{f_{ck}}$ values of the concretes were in the range of 0.73~0.90 and the changes had no effects on the *W/B* and unit binder contents. In all mixes, $f_r/\sqrt{f_{ck}}$ of concrete was higher than the predicted values of the coefficients of rupture of ACI 318-11 ($f_r/\sqrt{f_{ck}} = 0.63$); the average was 0.82, which was 30% higher than the ACI criteria.

In the case of concrete tensile strength (splitting tensile), there are no specifications, either in ACI or in any other standards, and the values are generally at the approximate levels of 0.08~0.14 of concrete's compressive strength (Ref.). The tensile strength (f_{sp}) levels of the concretes cured at 20°C were in the range of 3.6~4.6 MPa, which were at the level of 0.067~0.074 of the compressive strength, thereby showing a slightly lower strength range than the general tendencies. The results of non-dimensionalization with the 28 day compressive strength (f_{ck}) to analyze the

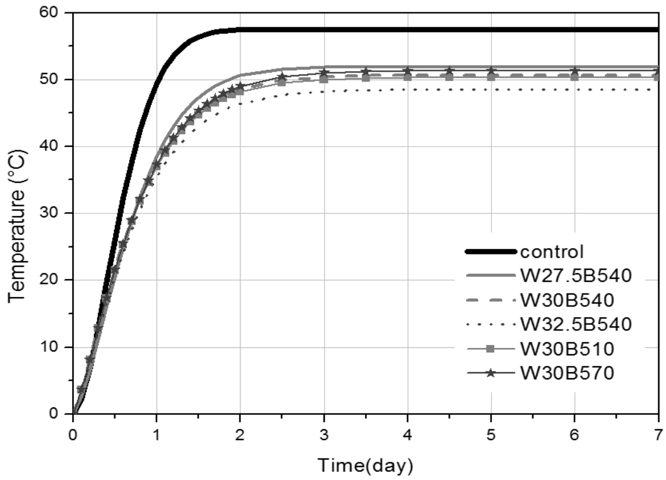


Fig. 6 Adiabatic temperature rise curves of concrete tested

Table 3 Temperature rise parameters in Eq. (1) determined from the adiabatic tests

	Control	W27.5B540	W30B540	W32.5B540	W30B510	W30B570
Q_∞ (°C)	57.54	51.935	50.67	48.506	50.284	51.289
r (°C /hr)	1.96	1.3519	1.3347	1.3137	1.3271	1.3005

effects of the *W/B* and unit binder content changes are shown in Fig. 5. According to the analysis, the tensile strength of the concrete was not affected by either the *W/B* or the unit binder contents.

3.5 Adiabatic temperature rise test

The hydration heat reduction of concrete is a factor that must be considered along with compressive strength performance in high strength mass concrete mixes. Adiabatic temperature rise curves are important indicators that show the thermal characteristics of concrete and are used as basic data for analyzing changes in concrete's internal temperatures after placement. Although adiabatic temperature rise curves can be obtained using Eq. (1) (KCI 2009), because errors in results can be large, depending on the mixes, results are generally obtained through adiabatic temperature rise tests.

$$Q(t) = Q_\infty(1-e^{-rt}) \tag{1}$$

Q_∞ : ultimate adiabatic temperature rise (°C)

r : temperature rise rate (°C /hr)

t : material age (day)

In the present study, adiabatic temperature rise curves were measured using 50-liter capacity experimental equipment from *T* Company in Japan and temperatures were measured for seven days considering the section where adiabatic temperature rises converge to be constant. As for maximum temperature rises, on the basis of the control mix, the mix models applied with ternary blended binders showed temperature drops of 9°C~5.6°C (approximately 12%) and the temperature rise rates (*r*), which are the values of slopes to the maximum temperature rise, were shown to be approximately 32% smaller as shown in Fig. 6 and Table 3. W32.5B540 specimens with the highest *W/B* showed the smallest maximum temperature rise, and higher binder contents were associated with larger maximum temperature rises. According to the results of the adiabatic temperature rise tests, the factor that affects maximum temperature rises the most sensitively was the *W/B*, and in all mix models except for the control mix model, temperature rise rate values were in the range of 1.30~1.35 (°C/hr) with no significant differences. According to the results of experiments on the mechanical characteristics of low heat cement-based ternary blended concretes and adiabatic temperature rises, mix designs suitable for changes in compressive strength and hydration heat temperatures considering curing temperatures can be made by adjusting the *W/B* and binder contents.

4. Conclusions

• The effects of the *W/B* and binder content on the compressive strength of the prepared concrete mixtures were more notable under the curing temperature of 5°C than under the temperature of 20 and / or 40°C

• The moduli of elasticity and rupture of the developed low-heat concrete could be conservatively predicted using the equations specified in ACI 318-11 provision.

•According to the developed low-heat concrete generated a lower temperature rise by approximately 12% than the control concrete. Temperature rise rates also showed approximate 32% lower than the control specimen made using 80% ordinary Portland cement and 20% conventional fly ash.

Overall, the developed low heat concretes based on the incorporation of low heat cement, fine-ground fly ash, and limestone powder can be practically useful for the application of mass concrete, in terms of high early-strength development and reducing hydration heat.

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