Investigation of the Mechanical Property of Low-Activation Concrete

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Abstract. This paper presents the strengths and fracture toughness of low-activation concrete (LAC) which can be used in the nuclear shielding structures and possibly in the nuclear decommissioning project. The research used four mixtures which include high alumina cement with 20%, 40% and 60% aluminum oxide as fine aggregate replacement and compared with those of normal concrete. All of the concrete strengths were evaluated and compared. The test results showed that LAC has high early strength and decays later due to conversion effect. The other fundamental mechanical properties will also be presented in this paper.

1 Introduction

Although the Fukushima nuclear power plant accident in 2011 has attracted plenty attentions in nuclear safety issue, nuclear energy still plays a significant role in the world due to its high cost-efficiency and little carbon emission. Therefore, the structural technology dealing with the nuclear facilities still needs to be innovated. Conventionally, heavy concrete is mostly used in biological shields or shielding walls in a reactor vessel^[1]. Kan and Pei^[2] have found that the compressive and tensile strengths of heavy concrete did not differ from those of regular mortar at the same water to cement ratio; however, the modulus of elasticity increases with the heavy aggregate aggregates. Kan and Yang^[3] later also investigated the toughness of heavy concrete strengthened by the inclusion of steel fibers. Recently, M. Kinno et al.^[4-5] has attempted to develop many mixtures of low-activation concrete and reported that the concrete including fused alumina aggregate and high alumina cement contribute led to the least activation among all the designated mixtures. Thus, it seems reasonable and necessary to access the feasibility to use this type of material in shielding structure design. Thus, the research investigated many engineering properties and strengths of low-activated concrete influenced by the various aggregates of high aluminum inclusion

compared. Mixtures of both concrete have a same water/cement ratio of 0.5. Table 2 shows the all mixtures. The amount of boron carbide B₄C is fixed at 10 % by weight for all LAC mixtures; while the amount of Al₂O₃ aggregates is varied. The low-activated concretes were designated with 20 %, 40 % and 60 % fine aggregate replacement by fused aluminum oxide (Al₂O₃ aggregates) by weight, to examine the effect of the high alumina cement and various amounts of Al₂O₃ aggregates on the mechanical properties of LAC. The LAC mix with 40% sand replacement by Al₂O₃ aggregates, for example, is specified as LAC40. It is noted that the unit weight of concrete increases with the Al₂O₃ aggregates, as shown in Fig. 3. And, it is found that the placement in concrete with 60% of Al₂O₃ aggregates by weight produced a harsh mix in workability.

Table 1. Constituents of cements.

Composition	Type I	HAC
Al ₂ O ₃	4.95	50.8-54.2
CaO	61.96	35.9-38.9
SiO ₂	20.42	4.5-5.6
Fe ₂ O ₃	3.09	1.0-2.2
MgO	3.29	<1.0
TiO ₂	-	<4.0
K ₂ O+Na ₂ O	-	<0.5
SO ₃	-	<0.1

2 Experimental Program

2.1 Materials and Mixtures

A Type I Portland cement and an alumina cement produced in France were used in this study. The typical constituent of both cements are shown in Table 1. The mechanical properties of concretes made were tested and

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2.1.1 High Alumina Cement

In high alumina cement, the predominant compounds are calcium aluminates; calcium silicates account for no more than a few percent. The calcium aluminates react with water and the primary product is calcium aluminate decahydrate (CAH₁₀) which has essentially a hexagonal crystal form. This material is unstable and changes to tricalcium aluminate hexahydrate (C₃AH₆) spontaneously. The process occurs at room temperature and is accelerated by an increase in temperature. The effect of conversion, as it is known, is accompanied by an increase in porosity and a decrease in strength.

2.1.2 Fused Alumina Aggregates

Unlike normal concrete, the main feature of heavy concrete is the inclusion of metallic fillers, which are usually ilmenite, limonite-goethite, serpentine, magnetite, barite, ferrophosphorous, steel aggregate and iron shot. In this study, fused aluminate aggregates were adopted as part of fine aggregates in concrete. It has an average grain size of 1 mm (ANSI No. 20) with a specific gravity is 3.90 and a hardness of 9 in Moh's scale.

2.1.3 Boron carbide

The ability of boron carbide to absorb neutrons without forming long-lived radionuclides makes it attractive as an absorbent for neutron radiation arising in nuclear power plants. Nuclear applications of boron carbide include shielding, control rod and shut down pellets. Within control rods, boron carbide is often powdered, to increase its surface area. In this study, boron carbide powder was used as part of concrete inclusion. It has an average grain size of 0.045 mm (ANSI No. 240) with a specific gravity is 2.52 and a hardness of 9.6 in Moh's scale.

Table 2. Concrete mixtures.

Component	NC	HAC		
		20%	40%	60%
Water	193 [§]	196	200	204
Cement	386	353	361	368
Aggregate	995	1012	1032	1054
Sand	762	619	474	322
B4C	-	39	40	41
Al ₂ O ₃	-	155	316	484
Water	193 [§]	196	200	204

[§]All units are in kg/m³. *Type I Portland cement concrete;
**high aluminum concrete.

2.2 Testing Specimens

Four types of specimens made from the above four mixtures were fabricated in this testing program. The ϕ 10 x 20 cm cylinders were used to determine the mechanical properties of concrete, including the compressive strength and tensile strength, modulus of elasticity and wave velocity.

3 Results and Discussion

The fundamental mechanical properties of concrete including compressive strength f_c' , splitting tensile strength f_t' and elastic modulus E_c are presented in Table 3 and discussed as following.

Table 3 Mechanical Properties of concrete

Mixture	day	f_c'	f_t'	E_c
		MPa	MPa	GPa
NC	28	30.1	1.98	20.7
	91	38.0	3.6	18.0
LAC20	28	43.7	2.97	24.4
	91	35.9	3.33	17.9
LAC40	28	50.2	3.42	26.9
	91	51.9	2.61	24.3
LAC60	28	44.3	2.16	27.3
	91	31.1	3.33	24.5

3.1 Compressive Strength

The compressive strength of LAC exceeds that of normal concrete and increases with Al₂O₃ aggregates for a given water/cement ratio. The compressive strengths for all mixes are shown in Fig. 2. It reveals that an increase in Al₂O₃ aggregates causes the increase in the

Fig. 2 Compressive strength of concretes

compressive strength. However, the mixture with an inclusion of 60% of Al_2O_3 aggregates by weight turns out the lower compressive strength and can be attributed to the bad workability for placing the concrete. The mixture with 40% of Al_2O_3 aggregates appears the highest strengths in all the curing duration. The compressive strength of LAC turns out higher in its earlier age (before 7 days of curing), but decays later due to the effect of conversion.

3.2 Wave Velocity

The mechanical properties of concrete can be estimated from its wave velocity by means of an ultrasonic wave tester. The test results revealed that the longitudinal wave velocity of LAC increases as the Al_2O_3 aggregates increases, as shown in Table 4 and Figure 3, which show a consistence with that of compressive strength of LAC. The mixture with 60% of Al_2O_3 aggregates by weight turns out the lower wave velocity and can be still attributed to the bad workability in placing the concrete. The mixture with 40% of Al_2O_3 aggregates appears the highest wave velocity before 28 days of curing duration. It is noticed that the wave velocity of all mixtures of LAC turn out decay in 91 day, which can be explained by the conversion effect.

Table 4 Wave velocity of concrete

Mixture	1 day	3 days	7 days	28 days	91 days
NC	3501*	4206	4344	4455	4481
LAC20	4561	4578	4604	4787	4021
LAC40	4760	4784	4823	4858	4397
LAC60	4633	4734	4792	4591	4330

*Unit: m/sec

Fig. 3 Wave velocity of concrete

3.3 Splitting Tensile Strength

The splitting test was used to determine the tensile strengths of concrete with various amounts of Al_2O_3 aggregates. Figure 4 shows that the tensile strength of NC is lower than LAC in 28 days, but becomes higher in 91 days of age. Furthermore, the tensile strength of LAC decreases as the Al_2O_3 aggregates increase. Obviously, the voids resulted from conversion dominate the tensile strength of LAC. The tensile strength reduces in 91 days of curing duration and decays more severe as the Al_2O_3 aggregates increases.

Fig. 4 Tensile strength of concretes

3.4 Elastic Modulus

Test results showed that the modulus of elasticity of LAC exceeds that of normal concrete and increases with Al_2O_3 aggregates for a given water/cement ratio. Figure 5 reveals that an increase in Al_2O_3 aggregates causes an increase in the elastic modulus, which appears consistent with that of compressive strength.

Fig. 5 Elastic moduli of concretes

4 Summary

LAC have higher compressive strength than normal for a given water/cement ratio. The compressive strength seems to be higher in the earlier age and decays after 7 days of curing. Concrete including 40% of Al_2O_3 aggregates as sand replacement performs the highest strength and workability as well. Elastic modulus of concrete appears to increase with the Al_2O_3 inclusion. The tensile strength seems to be decreasing with the increase of Al_2O_3 aggregates in concrete. The voids due to the effect of conversion do affect the mechanical properties of concrete.

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References

1. P. Lessing, *Developments in the Formulation and Reinforcement of Concrete* (Sidney Mindess, 2008)
2. Y.-C. Kan, K.- C. Pei and C.- L. Chang, J. NUCL ENG DES, **228**, 119-27(2004)
3. Yu-Cheng Kan, Hsuan-Chih Yang and Kuang-Chih Pei, Adv Mat Res, **512 - 515**, pp. 2908 – 13 (2012)
4. Masaharu Kinno et al., PROG NUCL SCI, **1**, 28-31 (2011)
5. Masaharu Kinno et al., *SMiRT 19 Proceeding*, (2007)