Experimental Investigation of a Recyclable Fly-Ash Concrete Pavement Having Moderate Slump

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Abstract

A high early strength concrete pavement incorporating a high volume of fly ash and a cement-replacement ratio of 0.4 has been developed. The pavement concrete consists of limestone aggregate and powder in addition to these cementitious materials. It was noteworthy that all components in the pavement concrete may be primary calcium materials for manufacturing Portland cement. The fly ash concrete was made of a low cementitious material ratio (*w/cm*=0.33) and very low water content (110 kg/m^3) to improve strength development at an early age. The pavement concrete, therefore, has a very low slump value of 2 cm (or lower), so the concrete was not widely employed in the pavement application. This study aims to develop a new recyclable fly-ash concrete pavement having moderate workability. The foci of the experimental investigation are to confirm the recyclability for cement manufacturing and to examine strength properties applicable to the practical use of the concrete pavement. This paper demonstrates that chemical and physical properties of the recycled cement meet the Japanese criteria. The test result shows that the workable pavement concrete achieved the minimum strength for passable pavement at the age of 7 days, and the specified strength at 28 days.

Introduction

Fly ash, the most produced byproduct of coal-burning power plants, has often been used for concrete structures in Japan to improve the durability and plasticity of concrete. In particular, considering the power supply problems in Japan, increased application of fly ash has become desirable. Though fly ash can decrease shrinkage and the possibility of alkali silica reactions (ASR), corrosion due to carbonation is a concern for reinforced concrete incorporating fly ash of a high replacement ratio to Portland cement. Concrete incorporating a high volume of fly ash is most applicable to rigid pavements because the general concrete pavements rarely use reinforcing bars. In particular, concrete incorporating fly ash of 50% or above by mass of cementitious materials is defined as high volume fly ash (HVFA) concrete (Malhotra and Mehta, 2008). Applications of HVFA concrete for pavement have been discussed in previous reports. Naik *et al.* (1994; 1995; 2002; 2003) examined the structural performance and durability of HVFA concrete pavement and evaluated the applicability for concrete pavement. Atis *et al.* (2002a, 2002b) also investigated durability and serviceability of HVFA concrete pavement. In addition, Atis (2005) compared the mechanical properties of workable and roller-compacted

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HVFA concretes. Das (2010) also examined the fundamental properties of HVFA concrete pavement and investigated its applicability for rigid pavement.

The authors have developed a fly ash concrete pavement made with limestone aggregate, and investigated various properties of the concrete (Yoshitake *et al.*, 2014). The pavement concrete is notable in that it can be reused for cement production. Our previous study confirmed the recyclability of the concrete (Yoshitake *et al.*, 2015). The fly ash concrete was made with a cement replacement of 0.4, and had adequate durability for paving. The concrete has very low workability, such as a slump value of 20 mm (or lower), so the concrete was not widely employed in the pavement application. The study focuses on a recyclable fly ash concrete having a moderate slump to increase pavement applicability. Mechanical properties and durability of the workable concrete are examined and discussed by comparing the properties of the low slump concrete. In addition, the recyclability for cement production is also confirmed in the experimental investigation.

Research Significance

The present study focuses on developing a recyclable fly ash concrete pavement having a moderate slump and confirming the recyclability for cement production. This paper presents chemical and physical properties of the recycled cement made from the concrete pavement. In addition, the paper shows fundamental properties of the fresh and hardened concrete pavement.

Materials

Type II fly ash (JIS A 6201, 2008) and an ordinary commercial Portland cement (JIS R 5210, 2009) were used in the experimental investigation. The type II fly ash has similar properties to class F fly ash defined in ASTM standard C618. It should be noted that the fly ash used in this study is from a different source than that of the fly ash used in the previous studies (Yoshitake *et al.*, 2014; 2015).

The fine and coarse aggregates in the concrete were crushed limestone sand (2.62 g/cm^3) and crushed limestone (2.68 g/cm^3) as in previous studies (Yoshitake *et al.*, 2014; 2015; 2016). To obtain a moderate slump (65 mm or higher), a high-range water-reducing admixture (*HRWRA*) was used according to the mixture proportion design of the pavement concrete. In addition, air entraining agent for fly ash (*AEA*) was added to increase air content. The fundamental properties of the cementitious materials and aggregate are given in Tables 1 and 2, respectively.

Mixture Proportions

The water-cementitious material ratio (*w/cm*) was increased to ensure the moderate slump. The *w/cm* ratio was designed as 0.4 for the workable concrete having the moderate slump. The study aims for a slump value of 65 mm (or higher) at 30 minutes after the concrete-mixing by referring to a Japanese standard (JIS A5308, 2014). The cement replacement ratio for the workable fly ash concrete was 0.4, as it was with the ratio of fly ash concrete having the slump of 20 mm (Yoshitake *et al.*, 2014; 2015). The mixture proportions of the tested concrete pavement are given in Table 3. Mixture M-3 shows a mix proportion of fly ash concrete having the moderate slump. For comparison, the mixture proportions of pavement concrete (M-0, M-1, M-2) reported in the previous study (Yoshitake *et al.*, 2015) are also presented in the table.

Table 1. Fundamental properties of cementitious materials

	Cement (C)	Fly ash (FA)
Density	3.15 g/cm^3	2.22 g/cm^3
Blaine fineness	3185 cm^2/g	3530 cm^2/g
Chemical Compositions		
CaO	64.3 %	1.33 %
SiO_2	20.4 %	63.9 %
Al_2O_3	5.7 %	22.54 %
Fe_2O_3	2.9 %	4.47 %
MgO	1.08 %	0.81 %
SO_3	1.89 %	0.27 %
Cl^-	0.017 %	N/A
Na_2O	N/A	0.53 %
K_2O	N/A	1.04 %
ig.loss	2.25 %	2.5 %

Table 2. Fundamental properties of aggregate

Aggregate	Density	F.M.	Size
Crushed limestone sand (S)	2.62 g/cm^3	2.75	5 – mm
Crushed limestone (G)	2.68 g/cm^3	------	20 – 5 mm

Table 3. Mixture proportions

Mix. ID	M-0 [a]	M-1 [a]	M-2 [a]	M-3
FA/cm	0.0	0.4	0.47	0.4
w/cm	0.33	0.33	0.29	0.40
W, kg/m^3	110	110	110	135
C, kg/m^3	334	200	200	202
FA, kg/m^3	0	134	174	136
LP [b], kg/m^3	50	50	0	0
S, kg/m^3	843	820	820	725
G, kg/m^3	1062	1033	1033	1138
$HRWRA$, kg/m^3	4.68	4.01	3.34	1.86
AEA, kg/m^3	1.23	1.20	2.00	1.27

a: previous study (Yoshitake, *et al.*, 2015); *b*: limestone powder.

Recyclability for Cement Production

Yoshitake *et al.* (2015) examined chemical and physical properties of the recycled Portland cement made by using fly ash concrete of the M-1 mixture. The previous study confirmed that the fly ash concrete pavement can be used in cement manufacturing as a primary calcium material. In addition, the present study aims to investigate the recyclability of the fly ash concrete having a moderate slump (M-3). The test procedures in this investigation were taken from test methods described in the previous study. The study examined chemical compositions by employing a Japanese standard test (JIS R5202, 2010) and X-ray fluorescence analysis. In addition, the study examined physical properties of the recycled cement by using a Japanese standard test (JIS R5201, 1997).

First, chemical compositions of the hardened fly ash concrete (M-3) were examined. Table 4 gives the chemical compositions of the workable concrete and the recyclable fly ash concrete (M-1). The results confirm that the fly ash concrete having a moderate slump has relatively high CaO (51.45 %) when it was made from a different source of fly ash. The present study used the fly ash concrete (M-3) in manufacturing cement clinker as a primary calcium material. By referring to general mineralogical compositions of cement clinker, a material design for recycled cement was determined. Table 5 gives unit-weight of each material used for the recycled cement. All mixtures and unit-weight were equal to the proportion of the clinker made from the fly ash concrete (M-1) reported in the previous study (Yoshitake *et al.*, 2015).

Table 4. Chemical compositions of hardened fly ash concretes (M-1, M-3)

(%)	ig.loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	others
M-1	39.43	3.25	1.05	0.55	50.28	0.47	0.20	4.77
M-3	38.52	2.69	0.75	0.41	51.45	0.54	0.16	5.48

Table 5. Materials for recycled cement clinker (M-1, M-3)

	M-1 & M-3
Fly ash concrete	848.7 kg/t
Fly ash	67.6 kg/t
Siliceous powder	58.0 kg/t
Iron oxide (Fe_2O_3)	9.7 kg/t
Gypsum di-hydrate	7.9 kg/t
Sodium carbonate (Na_2CO_3)	2.6 kg/t
Potassium carbonate (K_2CO_3)	5.4 kg/t

Table 6 summarizes chemical compositions of clinker and cement made from the fly ash concretes (M1 and M-3). The study estimates mineralogical compositions of the recycled clinker and cement by employing the Bogue formulae (Bogue, 1929). Table 7 gives the estimated mineralogical compositions. In addition, Figure 1 presents primary chemical compositions of the recycled cement by using data given in Table 6.

Table 6. Chemical compositions of recycled cements (M-1, M-3)

unit (%)	M-1		M-3		JIS R 5210 (2009)
	clinker	cement	*clinker*	cement	cement
ig.loss	*0.12*	1.21	*0.29*	1.14	< 5.0 %
SiO_2	*22.52*	21.45	*22.73*	21.77	N/A
Al_2O_3	*5.42*	5.16	*5.14*	4.99	N/A
Fe_2O_3	*2.96*	2.93	*2.85*	2.75	N/A
CaO	*66.04*	64.41	*66.46*	65.04	N/A
MgO	*0.83*	0.79	*0.90*	0.88	< 5.0 %
SO_3	*0.67*	2.57	*0.43*	2.24	< 3.5 %
Na_2O	*0.32*	0.31	*0.30*	0.26	N/A
K_2O	*0.48*	0.52	*0.33*	0.33	N/A
R_2O	*0.64*	0.65	*0.52*	0.48	< 0.75 %
TiO_2	*0.29*	0.27	*0.24*	0.25	N/A
MnO	*0.05*	0.05	*0.05*	0.04	N/A
P_2O_5	*0.16*	0.15	*0.12*	0.11	N/A
Cl	*N/A*	0.00	*N/A*	0.00	< 0.0035 %

The chemical and mineralogical compositions of recycled cement made from the workable concrete (M-3) were similar to the compositions of recycled cement (M-1). It is noteworthy that the chemical compositions of the recycled cement satisfied the requirements of Portland cement defined in Japanese criteria (JIS R 5210, 2009). This result confirms that, in addition to the currently used low slump concrete, the workable fly ash concrete can be also used in cement manufacturing as a primary calcium material.

Table 7. Mineralogical compositions of recycled cement (M-1, M-3)

unit	M-1		M-3	
(%)	*clinker*	cement	*clinker*	cement
C_3S	*55.1*	52.9	*57.9*	55.4
C_2S	*23.1*	21.6	*21.6*	20.7
C_3A	*9.4*	8.7	*8.8*	8.6
C_4AF	*9.0*	8.9	*8.7*	8.4

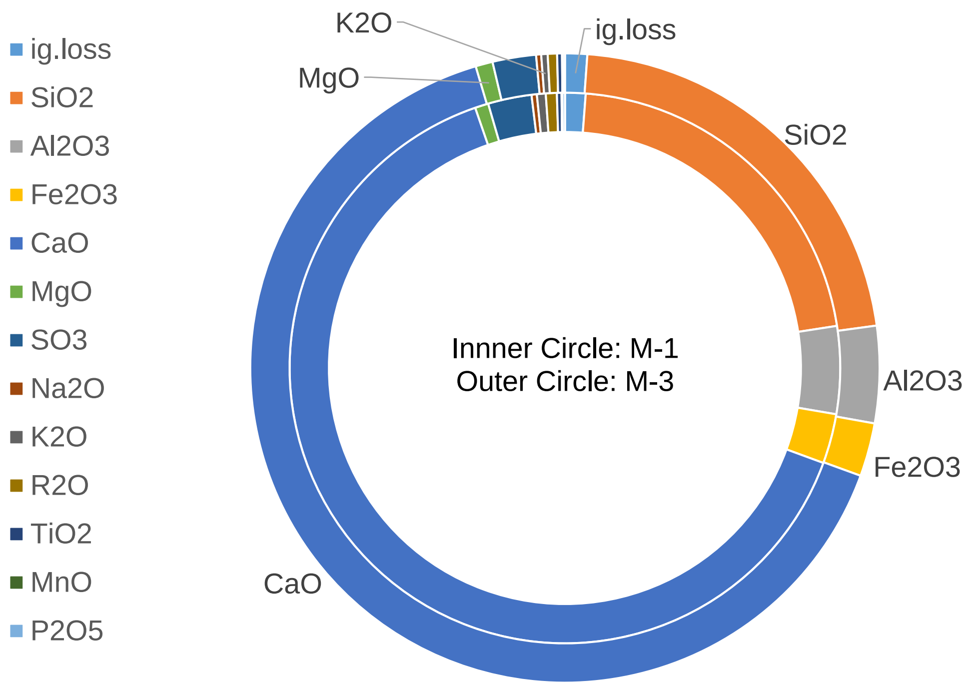


Figure 1. Chemical compositions of recycled cements (M-1, M-3)

To examine physical properties of the recycled cement (M-3), this study conducted the fundamental test given in a Japanese standard (JIS R5201, 1997). Table 8 presents the test results of the recycled cement (M-1, M-3). It was confirmed that the recycled cement (M-3) has adequate physical properties and meets the Japanese criteria (JIS R5210, 2009).

Properties of fresh and hardened concrete

Figures 2 (a)(b) illustrate the fly ash concrete of low slump (20 mm) and the workable fly ash concrete having a moderate slump, respectively. Initial slump values for the workable fly ash concrete ranged from 125-190 mm, though the value decreased to approximately 55-100 mm after 30 minutes. Further research should be conducted to improve the slump loss for the fly ash concrete.

These fly ash concretes indicated relatively lower air content than the conventional pavement concrete without fly ash. However, the air content met the minimum criterion of 3 percent or higher (JIS A1118, 2011).

Concrete pavement is passable for traffic when the flexural strength is equal to or higher than 3.5 MPa in Japan (JCA, 2010). Yoshitake *et al.* (2014, 2015) reported that the low-slump fly ash concrete made with the low water-cementitious material ratio (*w*/*cm*) of 0.33 achieved the minimum flexural strength at the age of 2 days. The workable concrete having a moderate slump was made with a higher water-cementitious material ratio (*w*/*cm*) than the low-slump concrete, so the strength properties should be investigated in order to assess practical applications. To examine the fundamental strength of pavement concrete, the study conducted the flexural strength test at the ages of 2, 3, 7, 28 and 91 days.

Table 8. Physical test results of recycled cements (M-1, M-3)

	M-1	M-3	JIS R 5210
Density	3.12 g/cm^3	3.13 g/cm^3	N/A
Blaine fineness	3320 cm^2/g	3350 cm^2/g	> 2500 cm^2/g
Residue of 90 μm sieve	0.6 %	1.1 %	N/A
Setting time start-end	1h. 53m. – 2h. 53m.	2h. 15m. – 3h. 12m.	60m. – 10h.
Soundness	Good	Good	Good
Comp. strength at 3 days	32.5 MPa	28.5 MPa	> 12.5 MPa
at 7 days	47.5 MPa	43.8 MPa	> 22.5 MPa
at 28 days	61.5 MPa	60.2 MPa	> 42.5 MPa
Flexural strength at 3 days	6.7 MPa	5.7 MPa	N/A
at 7 days	8.0 MPa	7.9 MPa	N/A
at 28 days	9.0 MPa	9.2 MPa	N/A
Flow value	208 mm	216 mm	N/A


(a) low slump concrete (M-1)

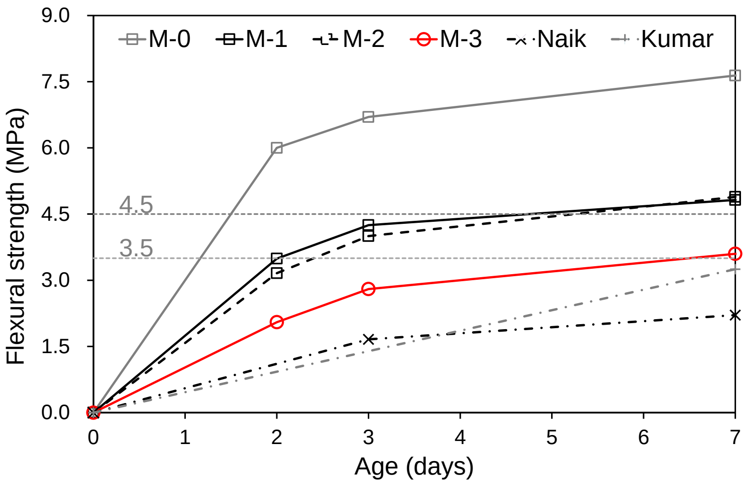

(b) workable concrete (M-3)

Figure 2. Fresh concrete

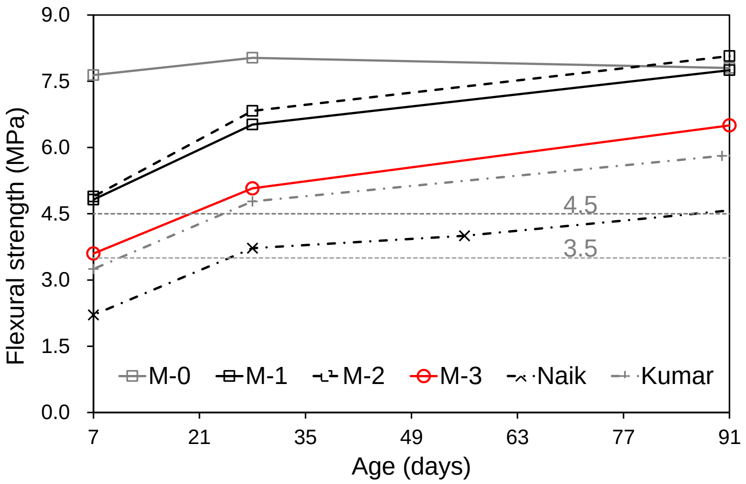
Figures 3 (a)(b) show the flexural strength at early age (0-7 days) and high later-age (7-91 days), respectively. For comparison, these graphs present flexural strength data reported by other researchers (Naik *et al.*,1995; Kumar *et al.*, 2007). The referenced tests were of flexural strength of pavement concrete made with a fly ash replacement ratio of 0.4 and a similar water-cementitious material ratio (***w/cm***). In addition, previous test data of low slump concretes (M-0, M-1 and M-2) are represented in these graphs (Yoshitake *et al.*, 2014; Yoshitake *et al.*, 2015).

Figure 3 (a) shows that the workable concrete (M-3) achieved the minimum flexural strength (3.5 MPa) after the age of 7 days. Therefore, the workable concrete pavement made with water-cementitious material ratio (*w/cm*) of 0.40 is not suitable for traffic until the age of 7 days. The gradual strength development of the workable concrete pavement should be noted. A pavement concrete called “1DAY-PAVE” in Japan has been developed in recent years (Noda *et al.*, 2012). The pavement concrete achieved the minimum strength at 1 day by employing a high early strength Portland cement. To improve the strength development of the workable concrete pavement (M-3) for practical applications, the use of a high early strength Portland cement may be preferable.

Figure 3 (b) confirms that the workable concrete (M-3) had a strength of approximately 5.1 MPa at 28 days and achieved the specified strength (4.5 MPa). It is noteworthy that the fly ash concrete (M-3) made with a unit cement weight of 200 kg/m^3 indicated the adequate strength at high later-age. The recyclable fly ash concrete having a moderate slump may be widely applicable for pavement constructions where applications of the low slump concrete are limited. Further research such as fatigue and abrasion resistance should be conducted to confirm the practical applications.



(a) early age (0-7 days)



(b) high later-age (7-91 days)

Figure 3. Flexural strength development

Conclusions

The present study investigated the recyclable pavement concrete incorporating fly ash with a cement-replacement ratio of 0.4, in addition to summarizing previous investigations. The foci of this study were to develop a fly ash concrete having moderate slump and to confirm the recyclability and fundamental strength. The conclusions of this investigation are summarized as follows:

1. To improve workability of recyclable pavement concrete, a fly ash concrete made with a water-cementitious material ratio of 0.4 and a cement replacement ratio of 0.4 was developed and tested. The pavement concrete had a moderate slump even at 30 minutes after the mixing of concrete.
2. The workable pavement concrete reached the minimum strength (3.5 MPa) for passable pavement at the age of 7 days, and achieved the specified strength (4.5 MPa) at the age of 28 days. The gradual strength development at early age should be noted for practical applications.
3. A Portland cement was made by using the fly ash concrete as a calcium material. The physical and chemical properties of the recycled cement were examined by conducting Japanese standard tests. The fundamental tests confirmed that the recycled cement meets the quality of ordinary Portland cement defined in Japanese industrial standards. The fly ash concrete having moderate slump can be also used in cement manufacturing as a primary calcium material.

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