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Division I

EFFECTIVENESS OF USING OF LIMESTONE AS CEMENT REPLACEMENT IN NUCLEAR RELATED CONCRETE STRUCTURES COMPARED TO TRADITIONAL SUPPLEMENTARY CEMENTING MATERIALS: A REVIEW

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ABSTRACT: For the purpose of reducing the CO_2 emission associated with the manufacture of Portland cement, limestone filler and traditional supplementary cementing materials, namely fly ash, slag cement, silica fume and metakaolin, are usually used as cement replacement materials. This paper compares the influence of different cement replacement materials on the hydration and compressive strength of concrete. The results reveal that the influence of limestone filler on the hydration of concrete mainly comes from the effect of dilution and heterogenous nucleation. However, the hydration of concrete containing traditional supplementary cementing materials are also additionally influenced by the cementitious and pozzolanic properties. Because of the lack of cementitious and pozzolanic properties, the replacement of Portland cement by more than 10% limestone filler would result in inferior compressive strength than control concrete, while this boundary for traditional supplementary cementing materials is usually 30%.

INTRODUCTION

Global cement production was estimated to be 4.0 billion tonnes in 2013 owning to the fact that concrete is the second most consumed material on earth after water (Ober, 2018) (U.S. Geological Survey 2014, European Federation for Precast Concrete 2014). Cement production has a significant environmental impact as it is responsible for 6-8% of worldwide manmade CO_2 emission (Benhelal, Zahedi, Shamsaei, & Bahadori, 2013) (Benhelal et al. 2013). One tonne of cement produces approximately 900 kg of CO_2 of which 450 kg is produced from the decomposition of raw materials and 360 kg from burning fuel (Benhelal et al., 2013) (Benhelal et al. 2013). The use of supplementary cementing materials has been a traditional approach to reduce the negative environmental impact of concrete. Limestone filler has been accepted as a cement replacement in many standards around the world. For example, the use of interground limestone as cement replacement has been accepted in many standards in Europe since 1960, Canadian Standard Association (CSA) (CSA, 1983) since 1983, European Standard EN 197-1 in (BS-EN-197-1, 2000) 2000 and ASTM C150 (ASTM-C150-04, 2004) in 2004. However, all of these standards have set a maximum interground limestone content which ranges from 5% to 15% (Tennis et al. 2011, Hooton et al. 2007) (Hooton, Nokken, & Thomas, 2007; Tennis, Thomas, & Weiss, 2011).

When replacing cement, limestone filler influences the behaviour of cement through physical and chemical effects. The physical effect is caused by (i) modification of particle size distribution, (ii) dilution and (iii) heterogeneous nucleation. Modification of particle size distribution and heterogeneous nucleation can improve the properties of concrete whereas dilution has adversely effect. The chemical effect of limestone filler is caused by the chemical reaction between limestone filler with monosulfate and calcium aluminate hydrate in the hydrated cement system.

The aim of this paper is to compare the effect of using limestone filler as cement replacement to that of supplementary cementing materials such as fly ash, slag cement and metakaolin on the properties and performance of concrete. In particular, this study aims to address the critical aspects pertaining to the hydration reactions and heat evolution, development of compressive strength at 28 days. Outcomes of this study will critically assess the viability of using limestone cement for critical structures and infrastructure pertaining to the nuclear industry.

PROPERTIES OF CONCRETE

Properties of concrete with Portland cement replaced by different supplementary cementing materials in literature is compared via a coefficient of property ratio. The property ratio of concrete with and without (control concrete) cement replacement material (namely, limestone filler, fly ash, slag cement, silica fume and metakaolin) is calculated by Eq(1). The ratio reflects the influence of a type of cement replacement material on different concrete properties, such as heat of hydration, setting time and compressive strength. On Figure 1 to Figure 4, a property ratio of 100% or 1.0 is shown as the dashed reference line. Data above the dashed line means that superior property is obtained compared to the property of control concrete, while data below the dashed line means the inferior property to the property of control concrete.

$$\text{Property ratio} = \frac{\text{Property of concrete with supplementary cementing material}}{\text{Property of control concrete}} \times 100\% \qquad (1)$$

Hydration

The influence of different cement replacement materials on the hydration of concrete is evaluated by the corresponding property ratios of initial setting time, hydration peak and hydration heat in the first 20 hours. All of the data presented in Figure 1 to Figure 3 is a result of aforementioned properties of concrete containing one type cement replacement material over the corresponding properties of control mix, namely concrete without any cement replacement material.

Figure 1 shows the influence of different cement replacement materials (i.e., limestone filler: (Aqel & Panesar, 2016; Fanghui, Qiang, Mutian, & Yingjun, 2016; Liu & Wang, 2014; Lothenbach, Le Saout, Gallucci, & Scrivener, 2008; Nocuń-Wczelik, Trybalska, & Żugaj, 2013; Thongsanitgarn, Wongkeo, Chaipanich, & Poon, 2014; Vance, Aguayo, Oey, Sant, & Neithalath, 2013; Yan, Mi, & Wang, 2014); fly ash: (Han, He, Zhang, & Liu, 2017; Han, Zhang, Liu, & Yan, 2016; Thongsanitgarn et al., 2014; Vance et al., 2013); slag cement: (Arora, Sant, & Neithalath, 2016; Han et al., 2017); silica fume: (Kadri & Duval, 2009); and metakaolin: (Cherem da Cunha, Gonçalves, Büchler, & Dweck, 2008; Vance et al., 2013)) on the hydration peak of fresh concrete, that is an indicator of the early-age hydration rate. Different impacts of cement replacement materials on the hydration peak are illustrated. In the cement replacement range of 5% – 50%, the incorporation of fly ash, silica fume and coarse limestone filler (fineness < 5000 cm^2/g) decreases the hydration peak of fresh concrete, while the incorporation of metakaolin increases the hydration peak because of the high aluminate content. Regarding slag cement and fine limestone filler (fineness > 10000 cm^2/g), the effect of the incorporation on the hydration peak varies, depending on the aluminate content in slag cement and the fineness of the limestone filler.

Figure 2 shows the influence of different cement replacement materials (i.e., limestone filler: (Aqel & Panesar, 2016; Bentz, 2014; Ezziane, Kadri, Hallal, & Duval, 2010; Moon, Oh, Jung, & Choi, 2017); fly ash: (Bentz, 2014; Gulbandilar & Kocak, 2013; Snelson, Wild, & O'Farrell, 2011; Yılmaz & Olgun, 2008); slag cement: (Ezziane et al., 2010); silica fume: (Gulbandilar & Kocak, 2013); metakaolin: (Snelson et al., 2011)) on the setting time of fresh concrete. The increase in the replacement of Portland cement by fly ash, slag cement, silica fume or metakaolin clearly increases the initial setting time of concrete relative to the control mix. To the contrary, the replacement of Portland cement by limestone filler decreases the initial setting time of concrete, regardless of the particle size of limestone filler. The increase of replacement level

up to 35% decreases the initial setting time of concrete relative to the control mix, which indicates the role of limestone filler as nucleation sites in accelerating the hydration of Portland cement.

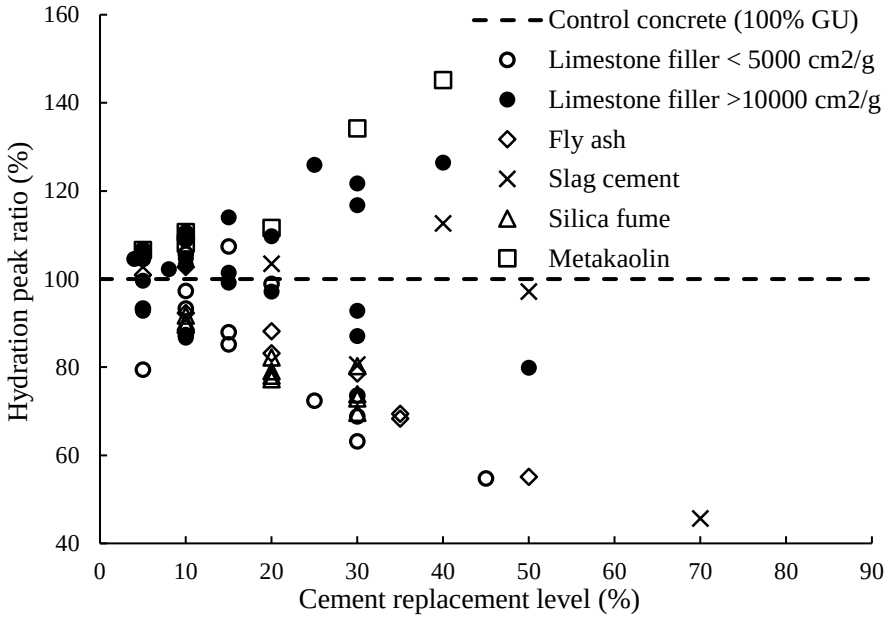

Figure 1. Hydration peak ratio of concrete with different cement replacement materials

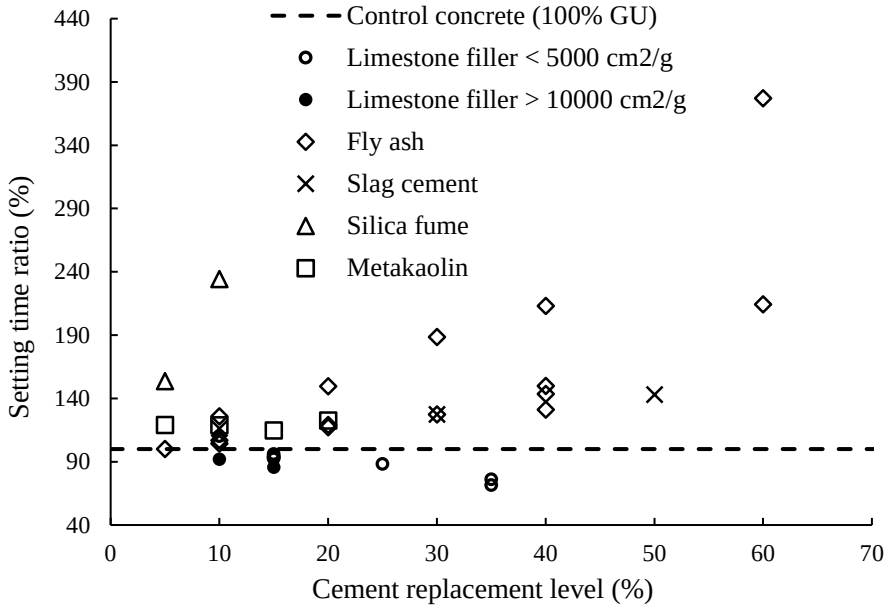

Figure 2. Setting time ratio of concrete with different cement replacement materials

Figure 3 shows the influence of different cement replacement materials (i.e., limestone filler: (Aqel & Panesar, 2016; Fanghui et al., 2016; Liu & Wang, 2014; Thongsanitgarn et al., 2014); fly ash: (Han et al., 2017; Han et al., 2016; Thongsanitgarn et al., 2014); slag cement: (Arora et al., 2016; Han et al., 2017); silica fume: (Bentz, Ferraris, Jones, Lootens, & Zunino, 2017; Kadri & Duval, 2009); metakaolin: (Cherem

da Cunha et al., 2008)) on the cumulative hydration heat in the first 20 hours of hydration. The replacement of Portland cement by silica fume or metakaolin increases the hydration heat in the first 20 hours. Silica fume accelerates the early stage hydration because of the fine particles size and the high pozzolanic activity. Concrete with the incorporation of metakaolin also increase the hydration heat due to the high cementitious and pozzolanic activities. The replacement of Portland cement by fly ash or slag cement, on the other hand, decreases the hydration heat in the first 20 hours because of the dilution effect. In terms of limestone filler, its incorporation increases the hydration heat of first 20 hours by 20% in the replacement range of 5% – 20% and decreases the hydration heat of first 20 hours by 20% in the replacement range of 20% – 50%.

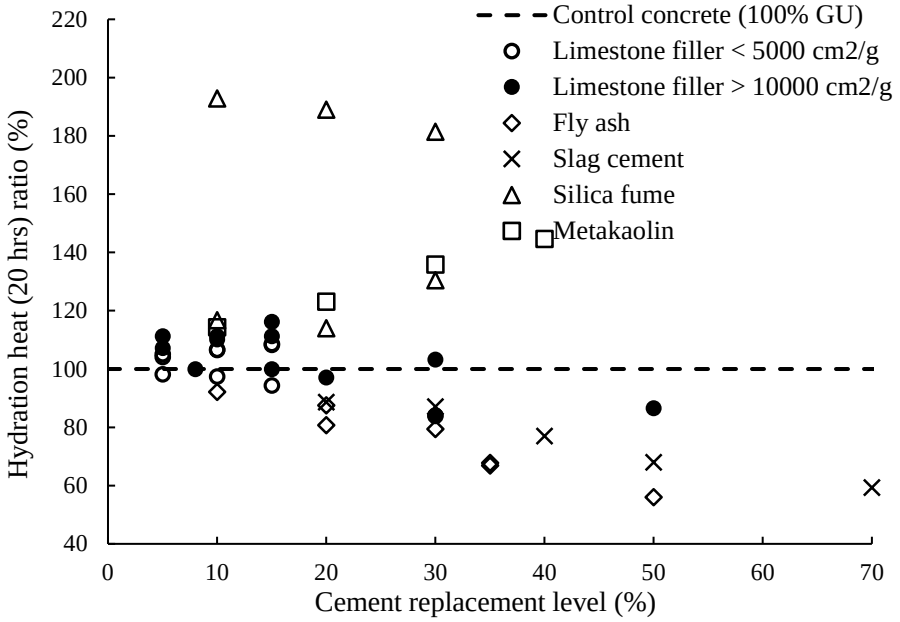

Figure 3. Hydration heat (first 20 hours) ratio of concrete with different cement replacement materials

Compressive strength

Figure 4 demonstrates the influence of different cement replacement materials (i.e., limestone filler: (Aqel & Panesar, 2016; Chen, Kwan, & Jiang, 2014; Diab, Elmoaty, & Aly, 2016; Ghrici, Kenai, & Said-Mansour, 2007; Meddah, Lmbachiya, & Dhir, 2014; A. A. Ramezanianpour, Ghiasvand, Nickseresht, Mahdikhani, & Moodi, 2009; Tsivilis, Batis, Chaniotakis, Grigoriadis, & Theodossis, 2000; Tsivilis, Tsantilas, Kakali, Chaniotakis, & Sakellariou, 2003); fly ash: (Fanghui, Qiang, & Jingjing, 2015; Kim, Davis, Ley, Kang, & Amrollahi, 2018; Poon, Lam, & Wong, 2000); slag cement: (Aldea, Young, Wang, & Shah, 2000; Güneyisi & Gesoğlu, 2008; Malhotra, 1989); silica fume: (Ahari, Erdem, & Ramyar, 2015; Bhanja & Sengupta, 2002, 2005; Madani, Norouzifar, & Rostami, 2018; Poon, Kou, & Lam, 2006); metakaolin: (Brooks & Megat Johari, 2001; Bucher, Diederich, Escadeillas, & Cyr, 2017; Poon et al., 2006; A. Ramezanianpour & Jovein, 2012)) on the compressive strength of concrete after 28 days of hydration. With 5% – 30% replacement of Portland cement by fly ash, slag cement, silica fume or metakaolin, concrete would achieve equivalent and superior 28-day compressive strength compared to concrete without any cement replacement material, due to the cementitious and pozzolanic properties of traditional supplementary cementing materials. To the contrary, concrete with the incorporation of limestone filler only provides equivalent or superior in the replacement range of 5% – 10%. Greater than 10% cement replacement by limestone filler or greater than 30% cement replacement by traditional supplementary cementing materials would reduce the compressive strength of concrete after 28 days of hydration.

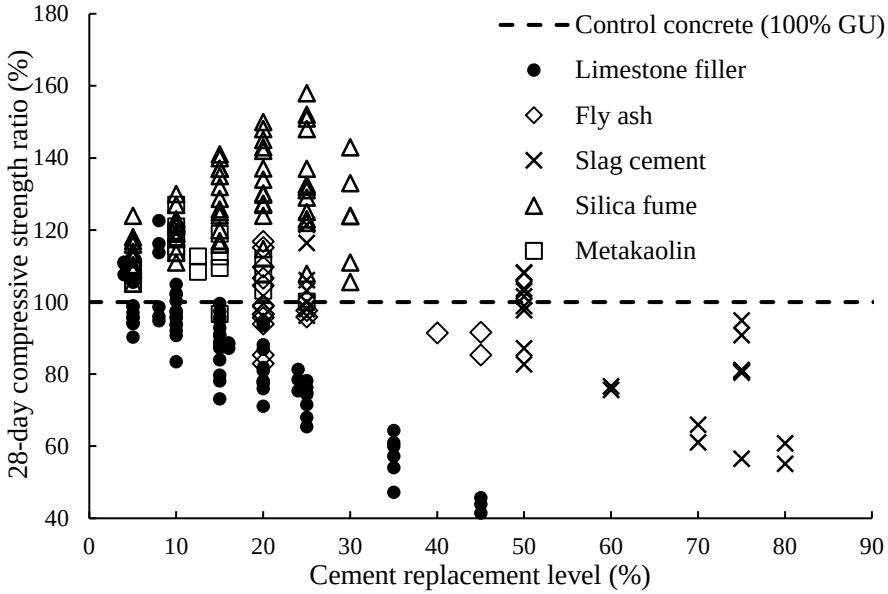

Figure 4. Compressive strength ratio of concrete with different cement replacement materials

CONCLUSIONS

Limestone filler as cement replacement has different performance on concrete properties than traditional supplementary cementing materials. The influence of limestone filler on the hydration of concrete mainly comes from the effect of dilution and heterogenous nucleation. However, the hydration of concrete containing traditional supplementary cementing materials are also additionally influenced by the cementitious and pozzolanic properties. Fine limestone filler and metakaolin has a similar effect of increasing the hydration. Incorporation of limestone filler decreases the initial setting time of concrete, while traditional supplementary cementing materials usually increases the setting time. Regarding the hydration heat of first 20 hours, the effect of limestone filler is less significant compared to traditional supplementary cementing materials. Because of the lack of cementitious and pozzolanic properties, the replacement of Portland cement by more than 10% limestone filler would result in inferior compressive strength than control concrete, while this boundary for traditional supplementary cementing materials is usually 30%. More studies are warranted to compare the durability of concrete containing limestone filler and traditional supplementary cementing materials.

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