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Utilization of industrial waste perlite powder in self-compacting concrete

Abdulkader El Mir Ph.D. student *, Salem G. Nehme Associate professor

Department of Construction Materials and Technologies, Budapest University of Technology and Economics, 1111 Budapest, Műegyetem rkp. 3, Hungary

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ABSTRACT

Different stages in the production of expanded perlite provide various types of waste by-products that could be used in the building industry, thus supporting a sustainable environment. In this study, the use of waste perlite powder (WPP) at a high content as a filler material in self-compacting concrete (SCC) was investigated. The combination of blast furnace slag cement as the main binder, along with metakaolin (MK) as a supplementary cementitious material (SCM), helped us produce several normally vibrated concrete (NVC) and SCC mixtures with low clinker content (190–220 kg/m^3). To ensure the appropriate rheological properties for SCC production, filler materials were added to the SCC mixtures, and the rheological properties of the fresh concrete and the mechanical and durability properties of the hardened concrete were investigated. The results indicated that WPP had a significant pozzolanic effect on the concrete microstructure, resulting in a positive impact on the compressive strength of the concrete. Furthermore, enhanced durability properties of SCC mixtures incorporating WPP was obtained.

1. Introduction

Worldwide, the cement sector is estimated to produce approximately5–8% of the total global anthropogenic carbon dioxide (CO_2) emissions. The CO_2 emissions from the cement industry can be divided into two sources. The first source is related to the energy required for burning the clinker (combustion). The other source is linked to the natural release of CO_2 associated with the decarbonation of the limestone under elevated temperatures (calcination). The total CO_2 emissions are estimated to be approximately 0.8 t per ton of clinker (Novak et al., 2005). Because of climate change, environmentally -friendly concretes have earned a great deal of attention over the last few decades, in terms of research and development. To produce cement, fossil fuels and waste are used as fuel for its fabrication. Today, the cement industry is working to reduce its carbon footprint by creating blended cement with supplementary cementitious materials (SCMs) (Mikulčić et al., 2016). The fastest and most effective way of reducing CO_2 emissions is by replacing the clinker with high amounts of SCMs (Mohammadi and South, 2015; Nagaratnam et al., 2015; Sethy et al., 2016). Blast furnace slags and fly ash, for instance, are the most common pozzolanic-replacing materials in high dosages. Limestone powder (LP) is usually used as a filler in the case of self-compacting concrete (SCC). Other pozzolanic materials used but in smaller dosages are metakaolin (MK) and silica fume; however, these materials are usually too expensive to have a cost-effective impact on reducing CO_2 emissions (Justnes, 2015). Therefore, there is a need to find other SCMs that could be applied in high amounts. SCC has an advantage associated with its casting mechanism; however, to meet workability and stability requirements, a high amount of binder content is needed. This creates a demand for an environmentally -friendly binder replacement. Earlier studies have tried to develop an eco-friendly version of the SCC. Wallevik et al. (2010) suggested an SCC classification for Eco-SCC based on the binder content, whereas Şahmaran et al. (2011) considered the efficacy of foundry sand as an economical and eco-friendly replacement material for SCC. However, more studies are necessary on alternative fillers that could deliver both high performance and durability in eco-friendly SCC products.

Perlite is a glassy volcanic rock that is considered a pozzolanic material because of its high SiO_2 and Al_2O_3 content (Rashad, 2016). Expanded perlite is produced from raw perlite rock and is applied as a valuable lightweight material. Hungary is one of the most well-known perlite-producing countries worldwide (U.S. Geological Survey, 2016). The physical and chemical characteristics of perlite facilitate its application in construction, horticulture, and other

* Corresponding author.
E-mail address: abdelkader.elmir@hotmail.com (A. El Mir).

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fields. Perlite powder or expanded perlite can be used in combination with aggregate or cementitious materials as an addition to or replacement for those materials in the building industry. Local perlite is produced in different particle sizes, resulting in a high amount of waste perlite powder (WPP). One study reported that during the grinding of raw perlite, a huge amount of WPP is collected and stored as fine-grained waste (Farkas et al., 2015). The authors suggested that such waste could be used as a filler material for SCC production because the particle-size distribution is appropriate. Several earlier investigations revealed the positive and negative effects of raw perlite powder and expanded perlite on the rheological properties of the fresh concrete and the mechanical and durability properties of the hardened concrete. (Rashad, 2016). Erdem et al. (2007) investigated the possibility of using perlite rock as a clinker replacement up to 30%, yet the results indicated that the replacement decreased the cement strength, although it could still be applied in the production of blended cement. Ramezanianpour et al. (2014) revealed that calcined raw perlite rock played a role in enhancing the durability of concrete. Bektas et al. (2005) showed that both raw perlite rock and expanded perlite have properties that can suppress the alkali–silica reaction. However, Yu et al. (2003) reported that natural perlite powder is characterized by its significant pozzolanic effect for concrete. In addition, Okuyucu et al. (2011) showed that natural perlite powder resulted in a considerable increase in the compressive strength of semi-lightweight concrete mixtures as compared to the control mixtures. However, there is little research on WPP as a filler for SCC. Therefore, the aim of this study was to investigate the potential of WPP in providing additional benefits other than its filling effect.

2. Research objective

In this study, the authors aimed to evaluate the performance of SCC with a high WPP content and a low clinker content. Analysis of the rheological properties of the fresh concrete was also carried out. Moreover, along with the filling ability provided by WPP for SCC, the pozzolanic effect of WPP on the mechanical and durability properties of SCC was also considered. MK powder was added as an SCM in addition to the main binder (slag cement) to evaluate its influence on the hardened properties independently. To do so, twelve concrete mixtures (4 NVC and 8 SCC) were produced, analyzed, and compared. The acronyms and definitions of the twelve different concrete mixtures studied are given in Table 1.

3. Experiments

3.1. Materials and mix design

Two series of combined NVC and SCC mixtures were designed and placed with common constant and variable parameters to obtain an objective evaluation of the fresh and hardened properties of the studied concretes. Local natural quartz river sand and gravel with a maximum nominal size of 16 mm were used in the mixtures. Blast furnace slag cement CEM III/A 32.5 R (C) with a compressive strength grade of 32.5 MPa and a clinker content in the range of 41–58 wt% in accordance with European Standard MSZEN 197-1 (MSZ, 2011) was applied for the present study. A commercially available MK powder was used as an alumino-silicate-based SCM. WPP originating from raw perlite rock was used as a filler for the SCC mixtures. Two types of WPP, which mainly differed in terms of their specific surface areas (WPP-C and WPP-SZ), were generated from cutting the raw perlite rock. LP was the non-pozzolanic filler applied in this study. The physical and chemical compositions of the fine materials are shown in Table 2, and grading fractions are provided in Fig. 1. A high-range-water-reducing admixture (HRWRA), Sika Viscocrete 5, was used to achieve the desired rheological properties.

To better imitate SCC types used in practice, several factors were considered in the mix design, including the total fine content (sum of cement, fillers, and SCM), SCMs, and filler type. The concrete type (NVC, SCC), cement (320, 360 kg/m^3) and SCM (none, 40 kg/m^3) dosages were set as variables. An aggregate particle-size distribution (three nominal grading fractions) was used according to European Standard BS EN 12620:2002+A1 (BS, 2008a): sand 0/4 mm (45%), small gravel 4/8 mm (25%), and medium gravel 8/16 mm (30%). The amount of water (W), 180 kg/m^3, and total fine content, 580 kg/m^3, were held as constant parameters. Two series of combined NVC and SCC mixtures sharing the same constant and variable parameters were compared in terms of their performance. The mixture compositions of all the studied concretes are summarized in Table 3. In this study, the cement was defined as the main binder,

Table 2
Chemical and physical characteristics of binders and filler materials.

Chemical composition	C	MK	LP	WPP-C	WPP-SZ
SiO_2	25.53	52.79	5.63	73.80	73.2
Al_2O_3	6.3	42.07	1.4	13.80	16.6
Fe_2O_3	2.29	1.25	0.9	1.57	2.6
CaO	55.59	0.37	50.32	1.17	1.06
MgO	4.05	0.38	0.65	0.11	0.2
SO_3	2.34	<0.01	0.08	–	–
K_2O	0.78	1.22	0.29	4.01	3.5
Na_2O	0.33	0.02	0.07	2.66	1.5
TiO_2	0.28	0.2	0.08	0.083	0.09
P_2O_5	0.03	0.06	0.02	–	–
Physical properties					
Specific gravity	3.1	2.6	2.69	2.33	2.33
Specific surface area (cm^2/g)	3450	15244	3470	843.3	4159
Loss on ignition (%)	2.15	1.59	40.55	2.8	1.21

Table 1
Notation and definition of concrete mixtures.

Acronym	Definition
NVC.320C	Normally vibrated concrete with 320 kg/m^3 of cement
NVC.320C.40MK	Normally vibrated concrete with 320 kg/m^3 of cement and 40 kg/m^3 of metakaolin
SCC.320C.260LP	Self-compacting concrete with 320 kg/m^3 of cement and 260 kg/m^3 of limestone powder
SCC.320C.220LP.40MK	Self-compacting concrete with 320 kg/m^3 of cement, 220 kg/m^3 of limestone powder and 40 kg/m^3 of metakaolin
SCC.320C.260WPP	Self-compacting concrete with 320 kg/m^3 of cement and 260 kg/m^3 waste perlite powder
SCC.320C.220WPP.40MK	Self-compacting concrete with 320 kg/m^3 of cement, 220 kg/m^3 of waste perlite powder and 40 kg/m^3 of metakaolin
NVC.360C	Normally vibrated concrete with 360 kg/m^3 of cement
NVC.360C.40MK	Normally vibrated concrete with 360 kg/m^3 of cement and 40 kg/m^3 of metakaolin
SCC.360C.220LP	Self-compacting concrete with 360 kg/m^3 of cement and 220 kg/m^3 of limestone powder
SCC.360C.180LP.40MK	Self-compacting concrete with 360 kg/m^3 of cement, 180 kg/m^3 of limestone powder and 40 kg/m^3 of metakaolin
SCC.360C.220WPP	Self-compacting concrete with 360 kg/m^3 of cement and 220 kg/m^3 of waste perlite powder
SCC.360C.180WPP.40MK	Self-compacting concrete with 360 kg/m^3 of cement, 180 kg/m^3 of waste perlite powder and 40 kg/m^3 of metakaolin