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Recycling of Concrete Demolition Waste Powder as a Sustainable Material in Portland Cement Pastes Modified with Nano-silica

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Abstract: In recent years, researchers dedicated themselves to explore the possibility of introducing concrete waste powder (CWP) into Portland cement as a sustainable material for Portland cement to reduce as possible the environmental pollution with this concrete demolition wastes. To optimize the effect of CWP on cement-based materials, this paper uses nano-silica (NS) to improve the hydration and mechanical properties of cement-based materials with CWP. Results indicated that after adding NS into CWP cement pastes, the setting time of cement pastes was significantly reduced, while the early rate of hydration and hydration heat increased. Besides, the mechanical strengths of the cement pastes increased as CWP replaced at the expense of the cement only up till 15 weights %, and then decreased. The addition of nanosilica (NS) can compensate the mechanical strength loss caused by CWP as supplementary cementing materials. The higher ratios of CWP than 15 weight % increased the pore volume or porosity. In contrast, NS in CWP blended cement significantly decreased the porosity, and increased the proportion of harmless pores. Hence, NS reduced the porosity, which in turn improved and enhanced the bulk density and mechanical properties. The optimum amount of NS is 2.5 weight % which resulted in the best results. The heat of hydration of the different cement batches in the two groups adversely affected with the incorporation of CWP, but little improved with NS. The obtained results were confirmed by the ultrasonic pulse velocity (USPV) test, where the cement batch PP15 (Group I) and PS2.5 (Group II) achieved the highest conformance.

Keywords: Nanosilica, concrete waste powder, density, porosity, strength, hydration, ultrasonic pulse velocity

1. Introduction

Due to overpopulation, rapid industrialization and urbanization, there is a surge in infrastructure development that led to the massive requirements of cement in the entire world. By the end of 2050, the cement requirement will arrive to 8-9 billion tons. This huge quantity of cement will definitely cause a harmful environmental impact. Hence, it becomes imperative to develop sustainable binders for construction [1-5]. On the other side, waste management is a global environmental problem that significantly impacts human, animal, and ecological health, which in turn it represents a broader challenge that affects the global economy. Accordingly, as the cement manufacture increased, a huge amount of wastes could be discarded. Therefore, shifting consumer behavior and waste generation rates are only expected to rise by time. The continuous growth of the major business related to energy as building or civil works has tremendously increased the volume of wastes which is becoming a significant threat to the ecosystem. So, the worldwide annual waste generation is expected to increase by 70-75% over the next 20 years, with vast implications for the environment and health [6-13]. Thus, it is requiring an urgent action for proper management and disposal [14,15]. The fast growing of the construction industry where the concrete is the most widely used construction material all over the world, in

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which Portland cement (PC) is the main binding material; the concrete consumes much more cement [16-18]. Consuming of natural resources often leads to a large amount of construction and demolition wastes. In some countries, more than two billion tons of waste concrete were generated [19-21]. The random disposal of concrete wastes will cause a heavy burden on the environment. To lighten the consumption of natural resources and the growing of concrete wastes, these concrete wastes must be recycled in useful applications [20,21]. Promotion of the concept of sustainable development, the reprocessing of these concrete wastes as aggregates has recently attracted our attention. This has great benefits to solve the natural resource deficiency and environmental pollution [22-24]. Many studies [23-27] have evaluated the mechanical properties and durability of the concrete waste aggregates (CWA). Results showed that the CWA decreased the performance of concrete. Others [23-27] used concrete waste as powder (CWP), where its main ingredients are unhydrated cement, sand and hydrated cement paste [24-28]. The CWP has a pozzolanic advantage [26-29] and filling effect [27-30]. This implies that the blending CWP as a supplementary cementitious material in cement is a potential method to reduce the consumption of cement. Moreover, the energy consumption, economy and costs of CWP are much too lower than cement. This is a contributor to the wide application of CWP in concrete. So, the CWP is an eco-friendly material because it emits CO_2 much lower than cement production [31-33]. The substitution of small amounts of CWP to concrete could minimize the global warming potential in concrete industry [31-34]. Results showed that the rate of hydration and cumulative heat of hydration with various fine concrete waste powders from different sources in the first 30 min were higher than that of the pure cement pastes [34,35]. The higher fineness of CWP leads to larger contact areas to water that positively reflected on the rate of hydration, while a lower heat of hydration after the first day [36].

Recently, nano-silica (NS) was used as one of cement-based materials for its superior physical and pozzolanic characteristics comparing with silica fume (SF), where the NS particles have some advantages of ultra-fine, high specific surface area and high activity [37-40]. NS has been successfully applied into cementitious materials to improve its hydration and mechanical properties. As NS particles have a high specific surface area, its use in mortar can significantly affect the fresh properties of cement mortar. The addition of NS to cement-based materials accelerated the hydration process of cement. Moreover, the specimens containing NS were more uniform and denser. Also, the NS enhanced the total heat evolution of cement pastes during the setting and hardening process [39-42]. The NS cement-based materials showed higher mechanical properties, i.e. NS can significantly improve the compressive strength and durability of cement mortar [43-46].

Hence, the influence of NS on the hydration behavior and mechanical properties of CWP-based cementitious mixes was studied. This paper used CWP to replace a part of cement (0--25 wt. %) and NS was added with a varying dosage (1-3 wt.%) to reveal its role in the mix. The obtained results were confirmed with ultrasonic pulse velocity test.

2. Experimental Procedure

2.1 Raw Materials

The used raw materials in the current study are Ordinary Portland cement (OPC Type I- CEM I 42.5 R) and CWP and NS. The OPC sample with a Blaine surface area of 3400 cm^2/g was delivered from Sakkara cement factory, Giza, Egypt, and its commercial name is known as “Asmant El-Momtaz”. The NS sample was provided from a local plant, Giza, Egypt. The concrete waste (CW) was first crushed using a suitable jaw crusher, and then was put into a laboratory ball mill for grinding, and sieved to obtain concrete waste powder (CWP) with a particle size ≤ 0.16 mm (Fig. 1). The specific surface area of The OPC and CWP samples are 3450 and 5685 cm^2/g, respectively.

Fig. 1 - Image of concrete waste powder (CWP)

The chemical analysis of the OPC, CWP and NS using the X-ray fluorescence (XRF) technique is shown in Table 1, while the mineralogical phase composition of the OPC sample [47,48] is summarized in Table 2. The physical properties of the raw materials are recorded in Table 3.

Table 1 - Chemical oxide composition of the raw materials, wt. %

Oxide Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	LOI
OPC	20.12	5.25	1.29	63.13	1.53	0.55	0.3	2.54	2.64
CWP	29.17	8.53	4.29	53.26	3.11	0.03	1.16	0.09	0.84

Table 2 - Mineralogical composition of OPC sample, wt. %

Phase Material	C_3S	β-C_2S	C_3A	C_4AF
OPC	46.81	28.43	5.90	12.56

Table 3 - Physical properties of the raw materials, wt. %

Properties Materials	Specific gravity	Density, g/cm^3	Blaine surface area, cm^2/g
OPC	3.15	1445	3450
CWP	2.12	1248	5685

2.2 Preparation and Methods

The OPC cement was partially substituted by CWP as in the first group (Group I), CWP and NS as in the second group (Group II). Group I as 100:0, 95: 5, 90:10, 85:15, 80:20 and 75:25 giving the symbols PP0, PP5, PP10, PP15, PP20 and PP25, respectively. Group II as 100:0:0, 95:4:1, 90:8.5:1.5, 85:13:2, 80:17.5:2.5 and 75:22:3 % having the symbols PS0, PS1, PS1.5, PS2, PS2.5 and PS3 as summarized in Table 4. Blending process of the various cement batches was done in a porcelain ball mill using five balls for two hours to assure the complete homogeneity of all mixes. The standard water of consistency [49] and setting time [50] of the various cement pastes were directly measured using Vicat Apparatus.

Table 4 - Mix composition of the raw materials, wt. %

	Mix Material	P0	PP5	PP10	PP15	PP20	PP25
Group I	OPC	100	95	90	85	80	75
	CWP	0	5	10	15	20	25
	Mix Material	**P0**	**PS1**	**PS1.5**	**PS2**	**PS2.5**	**PS3**
Group II	OPC	100	95	90	85	80	75
	CWP	0	4	8.5	18	17.5	17
	NS	0	1	1.5	2	2.5	3

Then, it was well mixed using the predetermined w/c-ratio (water of consistency), and poured into the prepared cement portion inside the mixer step by step. Then, the mixer was run for 5 minutes at an average speed of 10 rpm in order to have perfect homogenous pastes. Before casting of cement cubes, the moulds were covered with a thin film of a motor engine oil, to facilitate the release of the cement cubes from the moulds. The cement pastes were then casted into one-inch cubic stainless steel moulds (2.5 x 2.5 x 2.5 cm^3) using about 500 g from the cement batch, vibrated manually for three minutes, and then on a mechanical vibrator for another three minutes to remove all air bubbles tapped inside the cement pastes. The moulds were filled to the top surface and smoothed with a flat stainless steel trowel or a suitable spatula to obtain a flat and smooth surface [51]. After casting, they were covered with a wet sheet during the first 24 hours to prevent moisture loss. The moulds were then kept in a humidity chamber for 24 hours under 95 ± 1 relative humidity and room temperature (23 ± 1). The moulds were demoulded in the following day. Thereafter, the specimens were cured by the total immersion in water at an ambient laboratory temperature till the time of testing at

1, 3, 7, 28, 56 and 90 days. This is necessary for the cement cubes as it facilitates the proper hydration of cement phases.

The mechanical properties in terms of flexural and compressive strengths were carried out in accordance with ASTM-C293 [52] and ASTM-C109M [53], respectively. The rod-shaped samples were subjected to flexural strength (FS, MPa) using a simple beam with three points loading system (Fig. 2). The Compressive Strength (CS) of the various hardened cement pastes was measured using a suitable Piston.

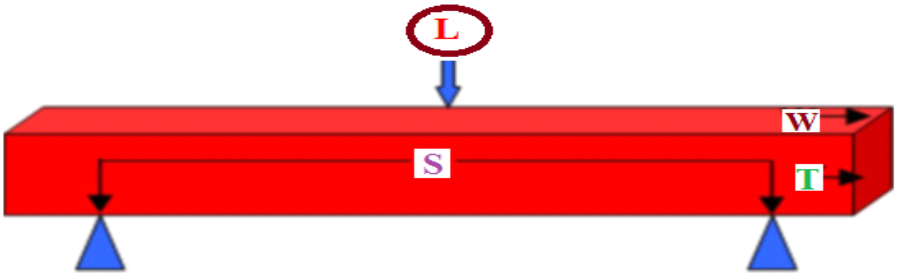

Fig. 2 - Schematic diagram of the flexural strength (L: beam or load, S: spam, T: thickness, W: width)

Thereafter, about 10 grams of the broken specimens after the compressive strength test was first well ground, dried at 105 ºC for 30 min. Then, it was placed in a solution mixture of 1:1 methanol: acetone to stop the hydration [47,48]. The bulk density and apparent porosity of the different hydrated cement batches [54-57] were determined. The final value for each parameter was reported by taking the average value of three specimen results.

The ultrasonic pulse velocity test (USPV) is a prominent non-destructive testing machine. It is mainly carried out to measure the propagation speed of an ultrasonic compression wave of different samples after 14 days of hydration, and to assess the uniformity and relative quality of existing structures and specimens [58,59]. The test was carried out on 1, 3, 7, 28 and 90 days for some selected samples. The prepared cement paste samples were subjected to ultrasonic pulse velocity (USPV) test in order to evaluate its physical properties in accordance to ASTM C597 (2002) [60], using a device with two transducers with a central frequency of 150 kHz noting that the USPV tests were done on three samples and the mean value was considered.

The heat of hydration of the prepared blended cement pastes has been experimentally investigated to confirm the obtained results [61,62]. Ultra-sonic pulse velocity (UPV) method (Fig. 1) is one of the prominent non-destructive testing (NDT) methods. It is mainly carried out to assess the uniformity and relative quality of existing structures and specimens. The test was carried out on 1, 3, 7, 28 and 90 days.

3. Results and Discussion

3.1 Characterization of OPC and CWP Samples

Table 5 shows the particle size distribution of both OPC and CWP samples. The two samples are containing no coarse particles, and the major content are fine particles as 99.98 and 99.97 % fine particles, respectively. The eggshell contains about 98.23 wt. % very fine particles. Sieve analysis proved that both samples have a very wide granulometry because its uniformity coefficient is greater than 200. Hence, they are siliceous [1,63].

Table 5 - Particle size distribution of the raw materials

Materials	Particle size distribution, %					
	>63	63-16	16-8	8-2	<2	Total
OPC	-	-	-	0.02	99.98	100
CWP	-	-	-	0.03	99.97	100

3.2 Consistency and Setting Times

Results of water of consistency and setting times (initial and final) of the OPC, OPC/CWP and OPC/CWP/NS are shown in Fig. 3. The water of consistency of OPC was 28.65 %. This value was increased by the addition of CWP, but decreased when NS was incorporated significantly. The increase of water of consistency may be due to that the CWP includes unhydrated cement which could be reacted with water to form hydration products [1,19,21]. Furthermore, the nucleation effect of NS, which provides a lot of nucleation sites due to the precipitation of hydration products that accelerate the hydration process [46].

On the other side, the setting times were also shortened and displayed the same trend as water of consistency [64,65]. This is essentially due to the faster creation of C-S-H gel and Ca $(OH)_2$. This in turn is the main cause of the

lowering of the setting times [64]. However, the setting time will increase with cement batches containing NS > 3%. This is mainly caused by the agglomeration of NS particles [65].

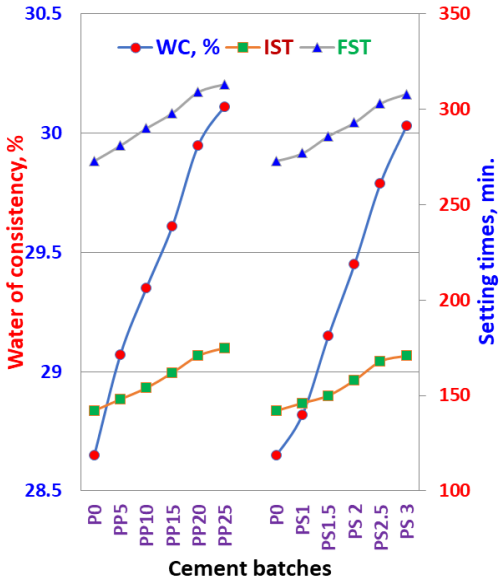

Fig. 3 - Water of consistency and setting times of the OPC containing variable of WCP (Group I) and WCP and NS (Group II)

3.3 Bulk Density and Apparent Porosity

The bulk density and apparent porosity of the various cement pastes incorporated different ratios of WCP (Group I) and NS (Group II) cured up to 90 days are shown in Fig. 4 and Fig. 5, respectively. Generally, the bulk density improved and enhanced as the curing times proceeded up to 90 days. This is mainly contributed to the normal hydration of the major phases of the cement, in addition to that of the unhydrated cement of WCP [66] as in (Group I). Moreover, the activation of NS increased the rate of hydration of the cement pastes [67] as in Group II. The bulk density continued to increase up till 15 wt. % WCP (P15), while up to 2.5 wt. % NS (PS2.5) at all curing times of hydration, and then decreased with any further addition of the two waste materials. Increasing of bulk density is essentially attributed to the micro-filling and pozzolanic effects of WCP, while the decrease may be due to the low activity of the WCP by which fewer hydration products were created, whilst the decrease of bulk density is principally due to the low activity of the WCP if compared with the blank (P0) [68, 69].

Increasing of the bulk density due to the addition of NS could be attributed to the positive and active role of NS particles [70,71]. The addition of further NS more than 2.5 wt. % led to an adverse effect on the bulk density. This often is due to the agglomeration of the excessive nanoparticles of NS, which consumes a lot of water and led to the inadequate hydration of cement [72]. There is an inverse relationship between bulk density and apparent porosity, where the apparent porosity decreased as the bulk density increased and vice versa [73-76].

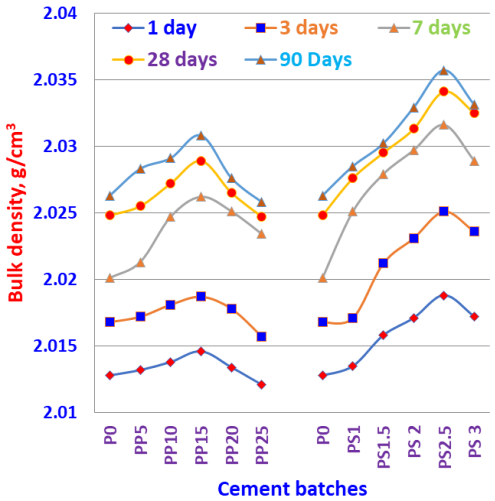

Fig. 4 - Bulk density of the OPC containing different ratios of WCP (Group I) and NS (Group II) hydrated up to 90 days

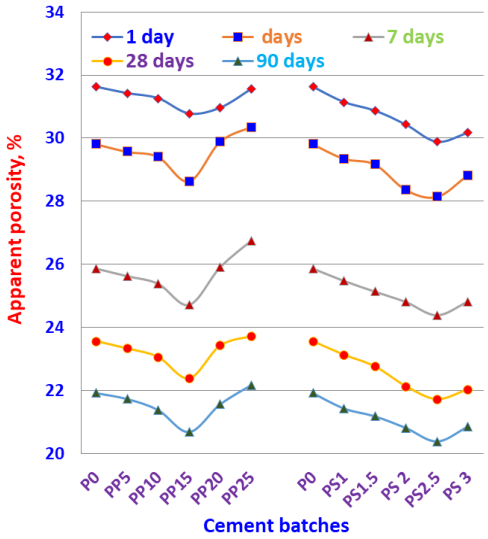

Fig. 5 - Apparent porosity of OPC containing different ratios of WCP (Group I) and NS (Group II) hydrated up to 90 days

3.4 Mechanical Strength

Fig. 6 and Fig. 7 illustrate the compressive and flexural strengths of the various cement batches cured up to 90 days. It is generally clear that the compressive strength continuously improved and increased with the hydration times up to 90 days with all mixes in the two groups. In Group I, this trend was continued only up to 15 % WCP (P15), and then decreased with any further increase (P20 and P25). The increase of compressive strength is mainly due to the micro-filling and pozzolanic effects of the waste powder, while the decrease may be contributed to the low activity of the WCP if compared with of the OPC (P0) which formed fewer hydration products in addition to the lowering amount of the main hydrating and cementitious material of the OPC [68,69,73-76].

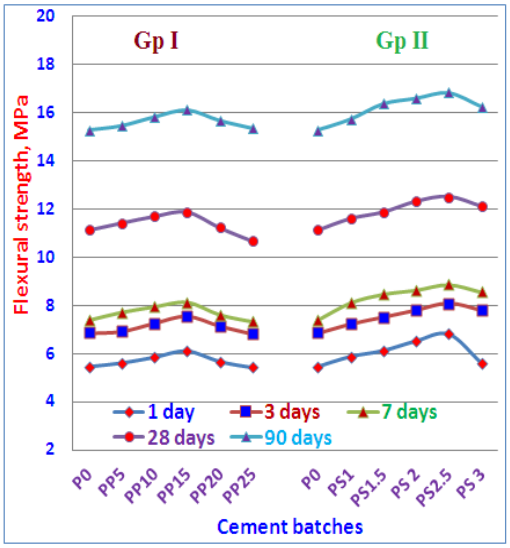

Fig. 6 - Flexural strength of OPC containing different ratios of WCP (Group I) and NS (Group II) hydrated up to 90 days

In Group II, the compressive strength was significantly improved and enhanced with the incorporation of NS only up to 2.5 % (S3) at all curing times, and then decreased gradually. The increment of compressive strength due to NS could be attributed to the positive and active role of NS particles [70-72]. With any further increase of NS more than 2.5 %, the compressive strength was adversely affected and decreased. This may be due to the agglomeration phenomenon of excessive NS, which consumes a lot of water and leads to inadequate hydration of cement. So, the internal defects of cement pastes increased causing the decline compressive strength [66, 73-76]. The cumulative pore

volume or porosity was reduced. Hence, the harmless level was significantly enhanced, i.e. NS has a positive effect on the hardening performance of cement pastes. This means that the NS refines the pore structure, which in turn results in improvements in the compressive strength. Some scholars [50,72,75] reported that the mechanical properties of cement-based materials are closely related to the pore structure. Therefore, NS improves the compressive strength of WCP blended cement because it plays a vital role in refining the pore structure. It can be concluded that the higher amounts of WCP and/or NS must be avoided due to its adverse influence.

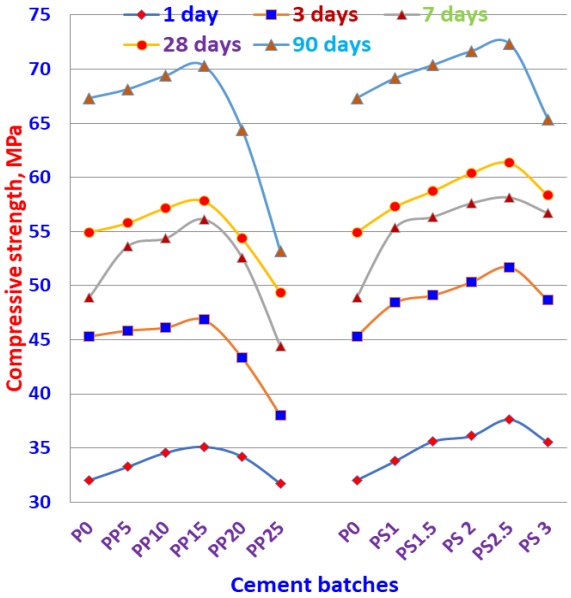

Fig. 7 - Compressive strength of OPC containing different ratios of WCP (Group I) and NS (Group II) hydrated up to 90 days

3.5 Ultrasonic Velocity Test

The ultrasonic pulse velocity graph of the blank cement pastes (P0) and the cement pastes blended with different levels of CWP (Group I) as well as those modified with NS (Group II) are graphically drawn versus the cement mixes in Fig. 8. In Group I, the USPV of the blank (P0) slightly increased up to 15 wt. % CWP, but more slight increase with further addition of CWP, i.e. the various constituents of blank (P0) and the other mixes did not affect by the ultrasonic pulse velocity [75,77]. The same trend was displayed by the mixes of Group II, but with little higher readings. Furthermore, the values of USPV of P25 (Group I) are the lowest, while those of S2.5 are the highest. Accordingly, the USPV test showed that the matrix conformities of Group II are well sticky and with a good quality than those of the Group I, i.e. a good uniformity with no cracks [77]. The gradual increase of pozzolanic reactions of CWP with the free lime coming from the hydration of β-C_2S and C_3S of the cement, is the main factor responsible for the high quality and uniformity of Group II [77-79]. Therefore, the results of USPV largely confirmed the obtained results. This means that the USPVvalues of samples incorporating CWP are lower than those containing NS. This confirms that the pozzolanic materials are the main cause of increasing the USPV [80]. Also, the data show an increase in USPV at enhanced contents of CWP and/or NS [75].

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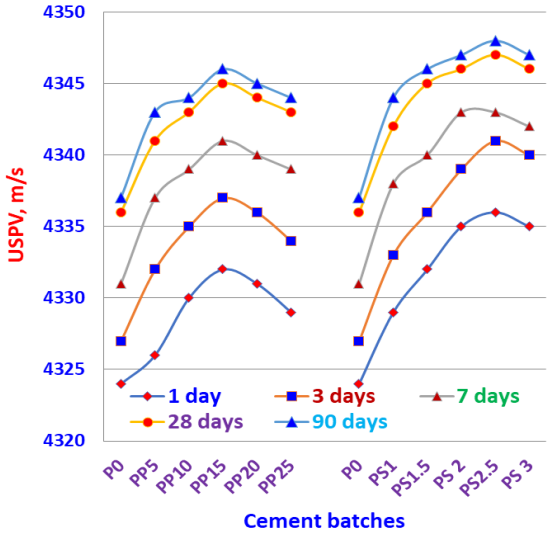

Fig. 8 - Ultrasonic pulse velocity of OPC containing different ratios of WCP (Group I) and NS (Group II) hydrated up to 90 days

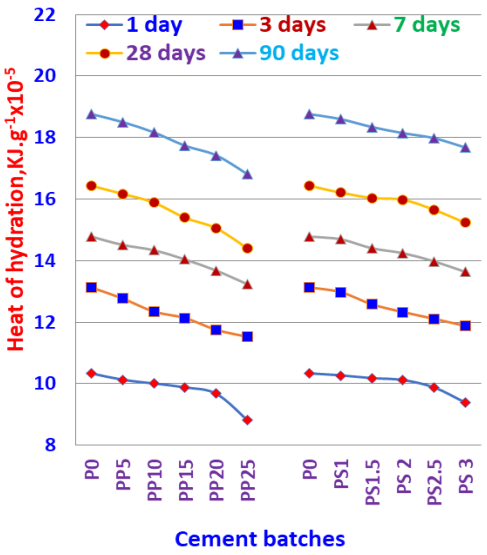

Fig. 9 - Heat of hydration of OPC containing different ratios of WCP (Group. I) and NS (Group. II) hydrated up to 90 days

3.7 General Discussion

The hydration process has gone when the cementitious material becomes in contacted water, where the free active CaO and gypsum in the components started to dissolve and soon react to form calcium trisulfoaluminate hydrate or ettringite (AFt) at the beginning of the hydration reaction. In addition, NS started to absorb Ca^{2+} and OH^- in the cement paste. This reduced the concentration of Ca^{2+} and OH^-, and promotes the hydration of C_3S [75] increasing the heat of hydration. When WCP replaced 30% cement content, the heat of hydration decreased. This is due to the dilution effect of WCP, which reduces the cement mass fraction, and the hydration reaction of WCP is not enough to offset the deceleration effect of hydration caused by the decrease of cement portion. Moreover, the maximum rate of the hydration heat increased with the increase of NS content. This demonstrated the promotion the hydration of cement by NS [80].

During hydration, the concentration of SiO_2 and Al_2O_3 in the reaction system is very low and the concentration of Ca $(OH)_2$ is close to saturation. The hydration products C-S-H gel and AFt adhered to the surface of C_3S [82], which hindered the development of hydration in a short time, i.e. the rate of hydration at a low level. Then, the rate of the hydration heat increased gradually. With WCP, the number of hydration products was decreased. Also, the incorporation of NS increased the rate of the heat of hydration with the increase of NS content, and the growth of C-S-

H and other hydration products accelerated the dissolution of C_3S [83-85]. Finally, the rate of hydration gradually decreased to the lowest level and tended to be stable.

As the content of NS increases, the heat of hydration of the cement pastes significantly increased. This is due to that the unsaturated bonds (≡Si-O, ≡Si-) on the surface of NS were related to the pozzolanic effect of Ca $(OH)_2$, and the pozzolanic reaction of NS increases the heat release rate of cement paste [84-87]. The reactions between NS and Ca $(OH)_2$ are shown in the following Equations:

$$\equiv Si\text{-}O\text{-} + H\text{-}OH \rightarrow \equiv Si\text{-}OH \text{ (react rapidly)} \quad (1)$$

$$\equiv Si\text{-} + OH \rightarrow \equiv Si\text{-}OH \text{ (react rapidly)} \quad (2)$$

$$\equiv Si\text{-}OH + Ca(OH)2 \rightarrow C\text{-}S\text{-}H \quad (3)$$

During the early ages of hydration, the early rate of heat of hydration of the pure OPC (P0 and/or S0) was higher than those of the WCP (Group I) as a whole, but lower than those mixed with NS (Group II). This demonstrated that WCP can delay the hydration process of cement paste and has a deterioration effect on hydration, while with NS, its excellent nucleation effect promoted the cement hydration. The cement paste setting time and early hydration indicate that 2.5 weight % NS has the best effect on improving the hydration of WCP blended cement pastes [37-39,86,87].

4. Conclusion

Both water of consistency and setting times of the various cement pastes increased with the addition of CWP, but little decreased with NS addition. The apparent porosity decreased with the increase of CWP content till 15 wt. %, and then increased with further addition, whilst the bulk density increases up to 15 wt. % CWP, and then decreased as clearly shown in Group I. In Group II, the apparent porosity improved and more decreased with NS content till 2.5 wt. %, and then reincreased. The same trend was displayed when the compressive and flexural strengths. The USPV as well as heat of hydration tests confirmed the obtained results.

The ongoing research must be intensified in terms of more comprehensive waste characterization, treatment/processing methods, and environmental implications. Further, the research should be expanded to cover more construction applications. Particular focus should be taken into consideration to research in waste recycling and developing necessary waste management politics helping to cross the hurdles and realize the successful implementation of waste recycling and reuse on pilot and/or industrial scales.

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