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INNOVATION OF USING WASTE MATERIALS AS A REPLACEMENT OF CEMENT IN PCC

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Portland cement (PC) is used in the production of Portland cement concrete (PCC) to construct many infrastructure components such as rigid pavements. This research aims at studying the effect of using common waste materials in Egypt as a replacement of PC in the production of PCC. Using waste materials in concrete production could be an effective measure in maintaining the environment, improving the properties of PCC, and reducing cost of production. Nowadays, pavement technologist and researchers had put their interests on nanotechnology. This paper outlines the innovation of using Nanotechnology-based waste materials as a replacement of PC to enhance the physical and mechanical properties of PCC. The experimental work, using waste materials such as ceramic waste (CW) and ground-granulated blast-furnace slag (GGBFS), was conducted in five phases. In phase 1 and phase 2, different rations were used for CW and GGBFS by weight of cement, respectively. In phase 3, the best three ratios of CW were used with the best ratio of GGBFS. In phase 4, different ratios of CW and GGBFS were used with a standard ratio of Un-Hydrated lime (UHL). In phase-5, various mix of CW, GGBFS and UHL were suggested based on previous results. Modified PCC mixtures were produced, tested and compared to the conventional concrete mixture. Results showed that the cost of PCC production is reduced by 34% in average comparing to the control mix.

Keywords: Nanotechnology, Rigid pavement, Ground-granulated blast-furnace slag, Ceramic waste, GGBFS, Un-hydrated lime.

1 INTRODUCTION

Portland cement concrete (PCC) is a most versatile construction material because it was designed to resist loads and environment changes with adequate strength and durability. This necessitates the use of special combinations of performance and uniformity requirements that cannot always be achieved using conventional constituents and normal mixing. Another challenge is to reduce production cost of PCC without reducing the concrete performance, especially for big projects (Aly *et al.* 2012, Meyer 2009). Waste materials could be a solution for this challenge as a replacement of Portland cement (PC) and could be also an effective measure in maintaining the environment, improving the properties of concrete, and reducing cost of production (Khan 2011, Fwa and Wei 2005, Umapathy *et al.* 2014).

The Egyptian ceramics industry is producing around 3 million tons/year of waste (about 15%-25% of total waste material). Ceramic waste (CW) is of generally two types: waste earthenware and cracked during the manufacturing process. CW is considered as non-hazardous solid waste and possesses pozzolanic properties (Dayalan and Beulah 2014, Lopez *et al.* 2007). On the other hand, ground-granulated blast-furnace slag (GGBFS) or steel slag, a by-product of steel making, is produced during the separation of impurities from molten steel in steel-making furnaces. The slag occurs as a molten liquid melt and is a complex solution of silicates and oxides that solidifies upon cooling (Sultan *et al.* 2014, Birgisson *et al.* 2010).

Un-Hydrated lime (UHL) is a Calcium oxide (CaO) as in clinker and cement that has not combined with SiO_2, Al_2O_3, or Fe_2O_3 during the burning process, because of under burning, insufficient grinding of the raw mix, or the presence of traces of inhibitors. Lime has been used for a very long time in construction and buildings. Lime is an industrial product obtained by calcination of limestone in a limekiln (Oates 1998). Researchers have found that nanomaterials have significant effects in improving the strength and durability of PCC.

This paper outlines the innovation of using Nanotechnology-based waste materials (CW, GGBFS and UHL) as a replacement of PC in different dosages to enhance the physical and mechanical properties of PCC that could be used as rigid pavements. Modified PCC mixtures were produced, tested and compared to the conventional concrete in terms of Index Tests and Advanced Tests. Index tests include mix workability, compressive and flexural strength, density and base-carbonation. Advanced tests include X-ray diffraction (XRD) and Scanning Electron Microscope (SEM). The purpose is to evaluate the mechanical properties at 7 and 28 days to achieve the optimum percentage of the partial replacement of cement with waste materials.

2 MATERIALS AND METHODS

The materials involved in this research are cement, coarse aggregate, fine aggregate and waste materials such as CW, GGBFS, and UHL. The properties of these materials are tested and tabulated. The American code for concrete mix, ACI-211-11, was utilized provision for construction of PCC. Samples of wastes were collected manually and freshly at the beginning of the experimental work and stored as per standard specification. Wastes were broken into particles in nanometer (10^9 scale). The reduction in size was verified using SEM. Cement "AL-MUMTAZ" 52.5 grades (ASTM Type II) was used. Coarse and fine aggregates are used as follows: fractions of max size 10 mm of SUEZ crushed dolomite rock, and fractions of max size 2.70 of BANI-SWIF fine aggregate river sand, respectively.

2.1 Waste Materials

2.1.1 *Ceramic waste*

The CW was obtained from recycled ceramic tiles supplied by "AL-FARAANA" factory in Egypt. Cracked pieces were crushed. At the laboratory, these wastes were ground with an air jet mill to obtain powder. The resulting powders were sieved through a 75-lm (200 mesh) sieve.

The ceramic powder includes nearly 92% pozzolanic materials, where Al_2O_3 and SiO_2 were the main components with higher characteristic peak values during analysis. These two minerals could react with $Ca(OH)_2$ in the cement paste to produce crystalline C–A–H and low density C–S–H gel, which can fill nano pores in concrete, increasing the bond strength between the interface of aggregates, decreasing the permeability and improving the durability of the concrete.

2.1.2 *Ground-granulated blast-furnace slag*

The GGBFS was supplied from various steel industries in Egypt with a specific gravity of 2.40. As a replacement for cement, the GGBFS can be used from 5% to 70% depending upon compressive strength requirement. The same slag can be used effectively when it is converted to nano size. This would improve the performance of the slag as the surface area increases. The size reduction was achieved by loading raw slag of 17.15 microns into the planetary ball mill and ground for 2½ hours. The reduction in size was verified using Particle Size Analyzer and was found to be 370 nm after grinding (size has been reduced to around 45 times than original value).

2.1.3 *Un-hydrated lime*

In the lime industry, limestone is a general term for rocks that contain 80% or more of calcium or magnesium carbonates, including marble, chalk, and marl. UHL can be used as a replacement of cement from 10% to 20% depending upon compressive strength requirement and it could be used effectively when it is converted to nano size. An increase in clinker un-hydrated lime reduces the total silicates ($C_3S + C_2S$). Both C_3S and C_2S are involved in the hydration to produce the C-S-H gel, which is the main strength-forming phase in hardened Portland cement concrete. Un-hydrated lime hydrates to form more of Calcium Hydroxide $Ca(OH)_2$ crystals. More UHL leads to increase the proportion of C_2S and decreases the proportion of C_3S in the clinker, which is a more important contributor for 28-day strength. C_3S is much more reactive than C_2S.

2.2 Experimental Investigation

2.2.1 *Mix types and proportion*

The experimental work, using CW, GGBFS and UHL as a replacement of PC, was conducted in five phases as follows:

- **Phase 1**: CW was used with 20%, 25%, 30%, 35%, 40% and 45% by weight of cement;
- **Phase 2**: GGBFS was used with 5%, 10%, 15%, 20%, and 25% by weight of cement;
- **Phase 3**: The best three ratios of CW, based on the results, were used in conjunction with the best ration of GGBFS, based on the results;
- **Phase 4**: Three different ratios of CW and GGBFS (25%, 35% and 45%) were used in conjunction with the standard ration of UHL;
- **Phase 5**: Based on results of previous phases, different three ratios of CW (20%, 30% and 40%) were used in conjunction with the best ration of GGBFS and UHL.

In addition to the above five phases, a control mix was also designed with zero wastes.

2.2.2 *Mixture design*

The mixture was designed according to ACI-211, and ASTM C 595 for Blended Hydraulic Cements. The binder content (450 kg/m^3), fine aggregate content (892.8 kg/m^3), coarse aggregate content (717.8 kg/m^3) and water–cement ratio of 0.48 were chosen to be constant. The workability of the fresh concrete was measured with a standard slump cone using the slump test according to ASTM C 143. The coarse and fine aggregates were mixed first, followed by addition of cement, wastes and water. Nanoparticles are not easy to distribute uniformly due to their high surface energy. In order to solve this problem, before adding any nano waste to the mixture, nanoparticles were stirred separately for approximately 2-minutes at high speed using water. After making sure that the particles have been completely dissolved in water, they were added to the mixture.

2.2.3 *Compressive and flexural strength*

The test specimens were cast in steel cubic molds (100 x 100 x 100 mm) and steel beam molds (150 x 150 x 750 mm). Specimens were compacted on a vibrating table. After approximately 24 hours, the specimens were removed from the molds. The concrete specimens were cured in water at 21^{o}C in cure tanks until the time of testing. Casting, compaction, and curing were accomplished according to ASTM C 192 and C 293. For each mix, cubic samples were tested to determine compressive strengths at 7 and 28 days of curing, and beams at 28 days of curing.

2.2.4 *Instrumental analyses*

The instrumental analyses tests were used to present the quality of concrete and changes in concrete dense after using wastes. The XRD and SEM give an indication about the mechanical properties of concrete functional in concrete chemical composition and pozzolanic reactions. X-ray diffraction (XRD) was carried out on a Philips PW3050/60 X-ray diffractometer using a scanning range from 2θ of 0º to 60º with a scanning speed of 1 sec/step and resolution of 0.05°/step. SEM can achieve resolution better than 1 nanometer.

3 RESULTS AND DISCUSSIONS

3.1 Index Tests

3.1.1 *Mixes workability*

The results of the flow table test showed that the workability of all mixes of phase 1 was decreased when compared to control mix. While the workability of all mixes of phase 2 was increased when compared to control mix. This is because of the water absorption nature. CW absorbs more water than GGBFS. For phase 3, when a part of GGBFS has been replaced by CW, the workability increases, as the water absorption property of CW is high compared to steel slag. Only lesser amount of water is left behind for the hydration of cement. For phases 4 and 5, UHL absorption is very low. Therefore, CW+UHL decreases workability when %CW increases; on the other hand, the workability is increased when using GGBFS+UHL. It is noteworthy that the slump value of control mix is 23 mm, where the specifications are in the range of 18-38 mm with average of 28 mm and standard deviation of 10 mm according to (ASTM C 143/ C143M -00). Consequently, all results are within the acceptable range with constant water per cement ratio.

3.1.2 *Compressive strength test*

The % change in compressive strength -- from an average of three cubic specimens -- for the best 40-70% replacement of PC in all phases is presented in Figure 1.

3.1.3 *Flexure strength test*

For each mix, cubic samples were tested to determine the flexure strengths at 28 days of curing. The flexure strength for each mixture was obtained from an average of three beams specimens. The % change in flexure strength for the best 40-70% replacement of PC in all phases is presented in Figure 2. As shown in the figures, the following conclusions can be drawn:

- For phase 1 mixes, compressive and flexure strengths decrease with increasing of CW, it is related to the CW works as a filler not as pozzolanic material as like GGBFS.
- For phase 2 mixes, strengths increase with 5% and 10% of GGBFS, then a reduction was noticed for 15% of GGBFS until 25% of GGBFS.
- Therefore, phase 3 mixes were selected to use 10%, 15% and 20% of GGBFS with three different percentages of CW as 20%, 30% and 40%. By increasing the percent of GGBFS with the same ratio of CW, strengths decrease.

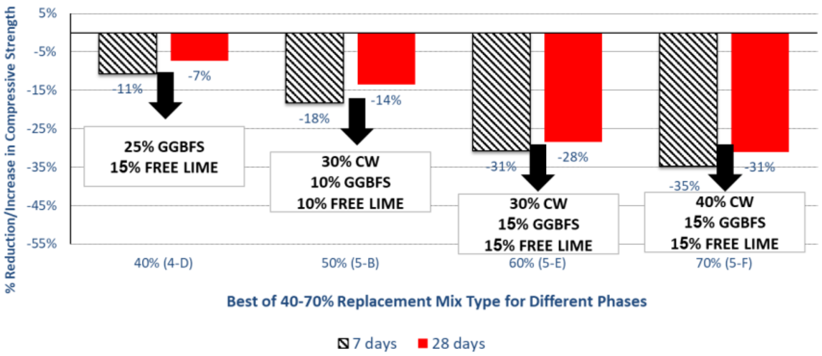

Figure 1. % change in compressive strength for the best 40-70% replacement of pc (all phases).

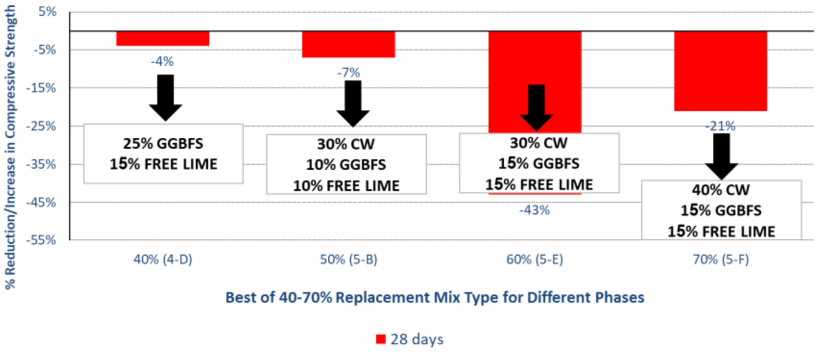

Figure 2. % change in flexure strength for the best 40-70% replacement of pc (all phases).

- Regarding phases 4 and 5, adding Un-hydrated lime, from 10 to 15 %, gives a good effect on both compressive and flexure strengths.
- For 70% cement replacement in (5-F) mix, only 31% reduction on compressive strength occurred by 20.9 N/mm2.
- For 40% cement replacement, mix has a minimum loss in compressive reading by only 14%. This returns to the percentage of CW as a pozzolanic relative to the percent of both GGBFS and Un-hydrated lime for continuing the interactions.
- The previous interpretation applies also on 50% and 60% replacement.
- Results of (5-E) and (5-F) mixes are very close despite 10% replacement difference.

3.2 Advanced Tests

To verify the mechanism predicted by concrete (compressive, flexural strength and base-carbonation) tests, X-ray diffraction and SEM Microscopy examinations were performed.

3.2.1 *XRD analysis*

Clearly, the (5-B) Mix showed the highest Portlandite {Ca (OH)2} peak intensity at 18.1^{o} 2θ. This peak decreases with the addition GGBFS, CW and UHL suggesting the pozzolanic reaction. A low intensity Portlandite peak was observed in case of cement concrete containing higher percent of GGBFS and UHL. This proved the highest pozzolanic reactivity of GGBFS. The XRD results are in the agreement with that of mechanical properties.

3.2.2 *SEM microscopy*

The microstructure of concrete containing 10% of GGBFS is higher homogenous and compacted than that of other mixes. Also, the interfacial transition zone of this mix is stronger than that of net concrete and concrete containing ceramic waste. This indicates the higher pozzolanic activity of GGBFS compared to CW.

4 ECONOMIC ANALYSIS USING WASTE MATERIAL

Based on the previous results, there are four suggested mixes, which are 40%, 50%, 60%, and 70% replacement of PC with different dosages of CW, GGBFS and UHL. The cost of each material per ton was identified and consequently the cost of each mix comparable to the control mix was calculated. It can be concluded that production cost could be reduced up to 18.5% in case of 70% replacement of PC with waste materials. Another cost comparison was made with the traditional flexible pavement; where the results showed that the construction cost was decreased by nearly 34% when using PCC with waste materials for (5-F) mix.

5 CONCLUSIONS

In trying to find possibility of reducing cost of rigid pavement construction using Portland cement concrete (PCC), waste materials were used by means of partial replacement of cement in PCC. Ceramic Waste (CW), ground-granulated blast-furnace slag (GGBFS) and Un-hydrated lime were used as waste materials in nanoparticles through five different mixes phases. Results showed that up to 10% of GGBFS, as a replacement of cement, gives good results in increasing mechanical properties of PCC depending on the high pozzolanic reactivity of GGBFS. Finally, results showed that the cost of PCC production with waste materials is reduced by 18.5% comparable to the control mix; and is reduced by 34% comparable to flexible pavement.

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