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Treatment and application of recycled concrete fines

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Abstract
The main objective of this research is to use recycled concrete fines (RCF) to replace part of the cement in new mortar recipes through a thermal treatment method. Cement is the most energy-consuming component of concrete, with high CO_2 emission during it manufacturing. If a certain amount of cement can be replaced by recycled concrete fines, it will increase the recycled material application level and thus help environment protection and natural resources preservation. There are several factors that can affect the compressive strength test results: cement type, water cement ratio, specimen size, mould type, the specimen surface, curing conditions, type of testing machine, the stress rate, etc. Mortar samples were tested by following the European standard EN 196-1 to keep the test conditions constant. RCF treated with different temperatures were used to replace part of the cement in the standard mortar samples containing either OPC or slag- or fly-ash blended cements.

Keywords: recycled concrete, mortar, OPC, blended cements, fine particles.

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Introduction

Shui et al. [1] studied the cementitious characteristics and the relative rehydration capability of dehydrated cement paste (DCP). The samples of hydrated cement paste (HCP) were grinded to particle sizes smaller than 75 µm. It was found out that the higher the dehydration temperature of DCP , the higher the required water of DCP to maintain the same standard consistency. The results show that the water of standard consistency increases from 32% for the samples at room temperature to 68% for the sample treated at 900 °C. The initial setting and final setting time decreased with the increase of temperature. For DCP samples treated at 800 °C, the initial setting time is as low as 17 min, which is slightly lower than the sample which was subjected to 900 °C. The compressive strength tests of DCP show that up to 800 °C, the compressive strengths of rehydrated DCP reach the maximum value for both early ages and 28 days. The authors concluded that the cementitious capability of DCP strongly depends on the dehydration temperature that the pre-heated HCP is subjected to. Shui et al. [2] did a lot of research on DCP, illustrating that the hardened cement paste subjected to a temperature of 500°C mainly composed of dehydrated C-S-H, C_2S, CaO, partially CH and non-crystaline dehydrated phases. If the pre-heated cement paste meets water again, the initial hydrated products of fine recycled concrete aggregates are recovered to original hydration products such as C-S-H gel, ettringite and CH. However, the microstructure of the rehydration products is looser than that of the ordinary cement paste.

Shui et al. [3] used DCP treated with the temperature of 650 °C along with $CaSO_4$, $CaCl_2$ and $Ca(OH)_2$ as the activator of fly ash; the results were impressive, the compressive strength of the new cementitious material with a certain proportion of DCP and fly ash being higher than 60 MPa when the original cement strength was 42.5 MPa. This research result is encouraging for future application of DCP in engineering practices. However, in their research, the samples were steam cured, which makes quite a difference from the samples cured under the room temperature. Another important factor was that in their research, pure cement paste was used for research purpose instead of real fine recycled aggregates from concrete. In the case of using real recycled concrete fines, there is a large amount of fine particles from silica sand and gravel mixed in the hydrated cement paste during the crushing process. The inactive quartz will reduce the starter effect of the pozzolanic reactions.

There are few studies focused on the recycled concrete particles smaller than 150 µm. Normally, recycled particles of this size are considered as the unusable fraction or of little use as filler [4]. Particles smaller than 150 µm are a similar size to cement particles; the main components are the cement hydration products, unhydrated cement, particles of original fine aggregates and crushed quartz particles from the original aggregates. There is a possibility to use recycled particles of this size as the replacement of cement in new concrete production. The rehydration of the dehydrated cement paste can obtain a certain degree of strength, especially when mixed together with fly ash [3].

Based on the previous description, it can be assumed that a binder system composed of thermally treated concrete fines (mainly composed of silica and dehydrated cement paste) and fly ash or slag can be a possible replacement for ordinary Portland cement.

RCF replacement tests

The material used for this study is a recycled concrete fine (RCF) fraction obtained from a prototype Smart Crusher SC 1 [4], with particle sizes under 150µm. All details about the generation and the properties of RCF can be found in [5]. The material was used as-generated (untreated RCF) and thermally treated at 500 and respectively 800°C (and termed 500 °C treated-RCF and 800 °C treated-RCF). These temperatures were chosen after performing a

Thermogravimetric Analysis on the sample and observing two major effects at these temperatures. These can be correlated to the decomposition of $Ca(OH)_2$ at just under 500 °C and the decomposition of $CaCO_3$ under 800°C, respectively. Both reactions produce CaO and liberate water, respectively CO_2 [7].

OPC replacement test

Untreated RCF, 500 °C treated-RCF and 800 °C treated-RCF were used to replace 10%, 20% and 30% of cement in the standard mortar samples (recipe according to EN 196-1). Commercial fly ash (termed in this study PKVA) was also used to replace the same amount of cement. EN 196-1 standard mortar was made as the reference. 7 days and 28 days flexural and compressive strengths were tested to measure the mechanical strength development.

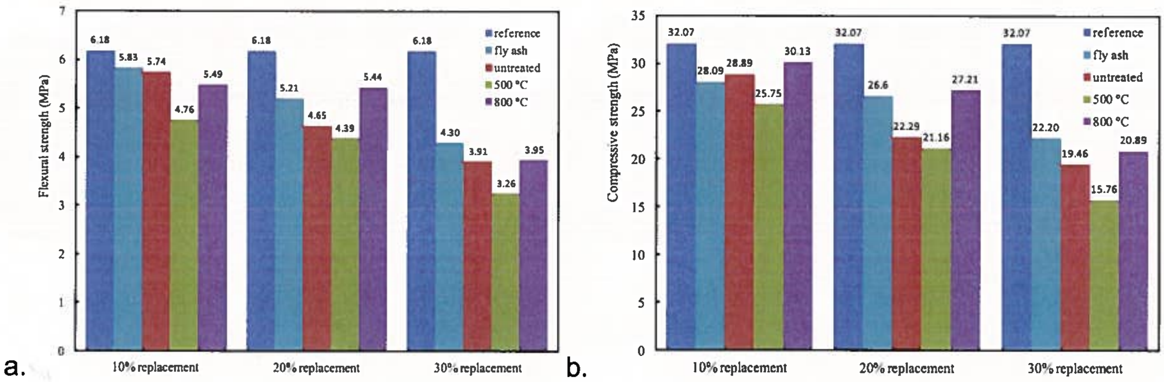

Figure 1. 7 days flexural (a) and compressive (b) strength of RCF-containing mortars at different replacement levels.

The consistence of the fresh mortar samples was determined by using the flow table test according to EN 1015-3. Original and thermally treated RCFs have higher water absorption than that of pure cement. In order to obtain a similar spread as the reference mortar, superplasticizer was used for the RCF 20% replacement and 30% replacement samples. The obtained mortar sample strengths are depicted in Figures 1 and 2 for 7 and 28 days of curing, respectively.

It is observed from Figure 1a that, with the increasing cement replacement ratio, the 7 days flexural strength of mortar samples decreases. The reference mortar has the highest 7 days flexural strength of 6.18 MPa. At 10% replacement ratio, 500 °C-treated RCF mortar has the lowest flexural strength among all; fly ash, untreated RCF and 800 °C-treated RCF obtained very good flexural strength when comparing to the reference mortar. At 20% replacement ratio, 800 °C-treated RCF obtained the highest flexural strength among all the substituting materials, which is 5.44 MPa. From 10% to 20% replacement ratio, the 800 °C-treated RCF achieved almost the same flexural strength. 30% of replacement ratio reduces the flexural strength significantly for all the mortars.

As can be seen from Figure 1b, the 7 days compressive strength of all the substitution materials decreases with the increase of the replacement ratio. 500 °C-treated RCF has the lowest 7 days compressive strength in all the replacement ratios. At 10% replacement ratio, 800 °C-treated RCF has a higher strength than the rest of the samples; however, it is still 6% lower than the reference. At 20% replacement ratio, 800 °C-treated RCF is still performing better than the other material but it is 15.2% lower than the reference mortar. It should be noted that the compressive strength decreases with less than the replacement ratio, which indicates that the RCF contributes to the development of strength. At 30% replacement ratio, all the substitute material decreased the compressive strength for more than 30% comparing to the reference; fly ash, in this case, has the highest 7 days compressive strength of 22.2 MPa, is 30.8% lower than the reference. Compared to the respective fly ash replacement instead of the pure OPC samples, all 800 °C-treated samples achieved almost the same 28-days compressive strength.

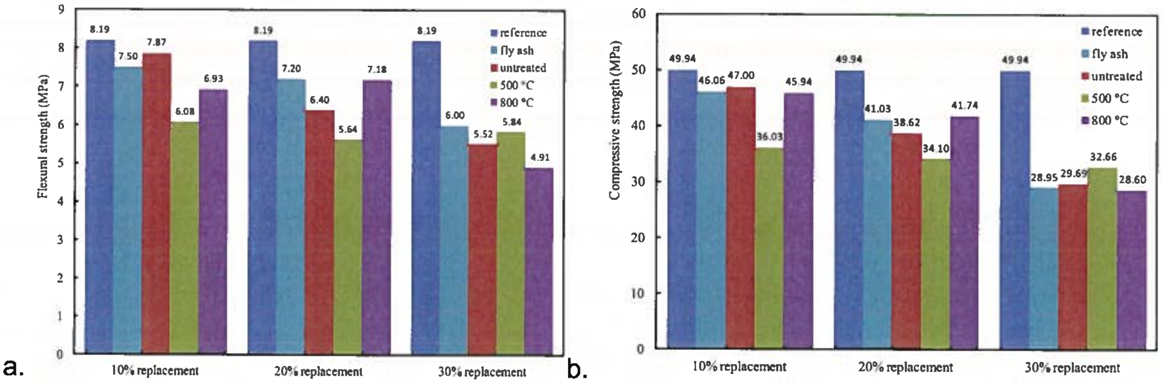

Figure 2. 28 days flexural (a) and compressive (b) strength of RCF-containing mortars at different replacement levels.

As can be seen from Figure 2a, the increased replacement ratio is no longer decreasing the 28 days flexural strength of the mortar samples. For instance, 500 °C-treated RCF at 30% replacement ratio, has the flexural strength of 5.84 MPa, which is higher than the 20% replacement one with 5.64 MPa. 800 °C-treated RCF has the 28 days flexural strength of 7.18 MPa at 30% replacement ratio, which is higher than the one of the 10% replacement sample. Untreated RCF at 10% replacement ratio is better than any other substitution material, with a flexural strength of 7.87 MPa which is only 3.9% lower than the reference mortar. At 20% replacement ratio, fly ash and 800 °C-treated RCF are both higher than 80% of the reference strength. This means that fly ash and 800 °C-treated RCF can contribute to the strength of the mortar samples.

At 10% replacement ratio, fly ash, untreated RCF and 800 °C-treated RCF showed good mechanical performances; the 28 days compressive strengths were all higher than 90% of the reference mortar and were enough to fulfill the specifications of the strength class 42.5 as required by the characteristic strength of EN 197-1. Untreated RCF, with the 28 days compressive strength of 47 MPa for 10% replacement ratio is the best one in all the replacement materials. At 20% replacement ratio, fly ash and 800 °C-treated RCF performed better than 80% strength of the reference mortar, which means they can both contribute to the mechanical strength of the mortar samples. 500 °C-treated RCF, on the other hand, is the worst at 10% and 20% replacement ratios; however, it is the best for the 30% replacement ratio. 800 °C-treated RCF has the equivalent 28 days strength of fly ash in all the tested replacement ratios.

The results can be explained as follows: PKVA fly ash, which has a low lime content, needs calcium hydroxide to accelerate the pozzolanic activity. It also can improve the consistence and cohesiveness of the fresh mortar paste. However, at 30% replacement, the generated calcium hydroxide is not enough to activate the fly ash, reducing the 28 days compressive strength by 42%. RCF, no matter untreated or thermally treated, needs more water than cement. At 10% replacement, RCF without thermal treatment acts mainly as filler material, which can provide nucleation sites for the cement hydration products. Moreover, calcium carbonate was found in RCF, which reacts with the aluminate phases in the cement [8]. At 20% replacement, the high water absorption value of the untreated RCF has caused a deleterious effect on the hydration process. 500 °C-treated RCF with dehydrated cement paste and CaO formed in it, increases the water absorption value. Although dehydrated cement paste can recover the original hydration products [2], it is speculated that the influence of the water demand is the dominant effect over that of the rehydration. 800 °C-treated RCF, with increased water demand, however, has more phases involved in the rehydration process, which can be beneficial for the compressive strength development.

Slag cement replacement test

In The Netherlands, more than 50% of the cement delivered to the market is CEM III, which has a relatively large amount of slag and small amount of cement clinker [9]. Slag has a certain level of self cementing ability because of the existence of lime and glassy SiO_2 in it. Cement is used to further activate the slag. 70% of slag mixed with 30% of cement was used as the reference. RCF, untreated and thermally treated were used to replace 33% of the cement in the slag cement blend (final mixture containing 70% slag, 20% OPC and 10% RCF). The water/binder ratio was kept at 0.5.

It can be seen from Figure 3 that the untreated RCF mortar has the lowest 7 days and 28 days compressive strengths. 500 °C-treated RCF increases the 7 days compressive strength by 7.5% and 28 days compressive strength by 14.7%. 800 °C-treated RCF has an even better performance in slag activation; the 7 days compressive strength increases by 8.8% and the 28 days compressive strength increases by 20.1%.

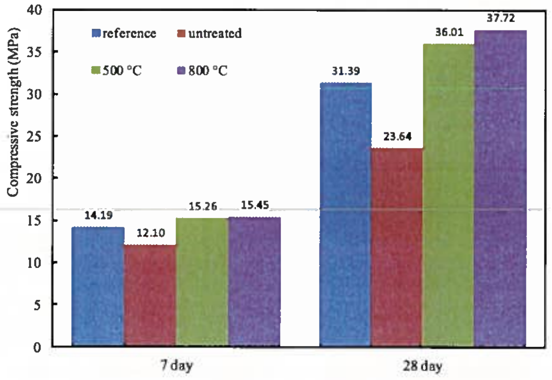

Figure 4. 3 7 days and 28 days compressive strength of slag blended cement mortars.

It is proven in this research that thermally treated RCF can be used to activate slag. Untreated RCF, without lime in it, has a detrimental effect to the mortar strength. 500 °C and 800 °C-treated RCF, containing free lime, have an activation effect on the slag, creating the alkali environment for the pozzolanic reaction at the beginning of the reaction. This leads to the higher compressive strength than the reference mortar samples.

Combining thermally treated RCFs with fly ash

Dehydrated cement paste was found to have an activation effect on fly ash [3]. In this research, 800 °C-treated RCF was combined with PKVA fly ash to replace cement in standard mortar samples. It was observed that 800 °C-treated RCF could decrease the fresh mortar consistence. When it was used to replace 20% of cement, superplasticizer was used to achieve good fresh mortar properties. Fly ash, on the contrary, has the property of increasing the fresh mortar properties when used in concrete [8]. Moreover, the free lime existing in 800 °C-treated RCF is believed to activate the PKVA fly ash. 10% 800 °C-treated RCF+10% PKVA fly ash were used together to replace 20% of cement in the standard mortar.

The fresh mortar consistence was tested by the flow table test; the spread of the 10% 800 °C-treated RCF+10% PKVA fly ash mortar sample was 141 mm compared to 139 mm of the reference sample. It can be concluded that 10% of PKVA fly ash can fully compensate the fresh mortar flowability loss caused by 10% 800 °C-treated RCF. Therefore, using 800 °C-treated RCF along with PKVA fly ash can increase the cement replacement ratio without losing flowability.

Mortar samples obtained by replacing cement by 20% of 800 °C-treated RCF and by 20% of PKVA fly ash respectively are also used for comparison. The 7 and 28 days flexural and compressive strengths are presented in Figure 4. It can be seen from Figure 4a that the 7 days flexural strength of the RCF + fly ash sample is the lowest one among all the samples. The 7 days flexural strength is reduced by 36.7% compared to the reference. However, the RCF + fly ash sample obtained very encouraging 28 days flexural strength of 7.19 MPa. This value is only 12.2% lower than the reference and is equal to the 20% RCF sample. It is illustrated in Figure 4b that the 7 days compressive strength of the RCF + fly ash sample is 38.1% lower than the reference sample. It is also much lower than the 20% RCF and the 20% PKVA fly ash samples. The 28 days compressive strength of the RCF + fly ash sample is 41.14 MPa which is 17.6% lower than the reference mortar. All of the three 20% cement replacement samples showed almost identical 28 days compressive strength results.

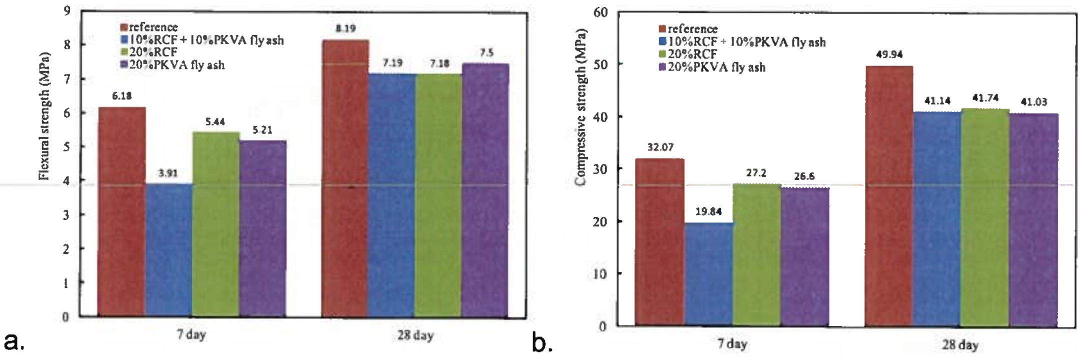

Figure 4. 7 days and 28 days flexural (a) and compressive (b) strength of the reference, 10% 800 °C-treated RCF+10% PKVA fly ash, 20% 800 °C-treated RCF and 20% PKVA fly ash replacement mortars.

Conclusions can be made based on the experiment result as that: PKVA fly ash is able to compensate the fresh mortar flowability loss caused by 800 °C-treated RCF. Using 10% 800 °C-treated RCF + 10% PKVA fly ash together can lead to a large decrease of the mortar sample 7 days flexural and compressive strengths. However, the 28 days flexural and compressive strength were good enough for encouraging the use of this mix of materials. This was to be expected, because substituting 20% of PKVA fly ash or RCF lead to very similar 28 days strength results.

Conclusions

In this research, laboratory made concrete was used to mimic the concrete recycling process. A specially designed smart crusher prototype was used to separate cement paste from concrete aggregates. The obtained recycled concrete aggregates were collected and separated into different fractions based on particle size. Particles under 150 μm were used for thermal treatment.

The thermal treatment can dehydrate the cement paste portion within the RCF, which can liberate the cementitous ability of RCF. When the thermal treatment temperature was selected as 500 °C, the major phase changes were the dehydration of the C-S-H gel, ettringite and the dissociation of most of the portlandite. When the thermal treatment temperature was increased to 800 °C, calcite also decomposed to lime and carbon dioxide. α–quartz undergoes a phase transformation to β-quartz at about 573 °C and is recovered to α–quartz again when cooled down to room temperature.

It was demonstrated that untreated RCF and 800 °C-treated RCF can be used in mortar samples up to 20% replacement ratio without causing large detrimental effects on the mechanical properties in hardened state. At 10% replacement ratio of cement, there was no evident decrease of the mortar spread. The 90% CEM I 42.5 N cement and 10% untreated RCF or 800 °C-treated RCF can still be categorized as strength class 42.5 according to the European standard EN 197-1. The performance of 800 °C-treated RCF was also compared with class F fly ash. It was found that 800 °C-treated RCF had equivalent mechanical performances as fly ash. The only difference is that 800 °C-treated RCF decreases the mortar sample fresh properties, therefore superplasticizer was used to obtain the same flowability. 500 °C-treated RCF was found not be suitable to use as cement replacement because of the detrimental effect on the mortar strength. All the cement substitution materials showed significant negative effect at 30% replacement ratio because of the water absorption value and the dilution effect to the cement.

Thermally treated RCFs (both 500 °C- and 800 °C-treated RCF) showed an activation effect on slag. It was found that 10% 500 °C-treated RCF and 800 °C-treated RCF can increase the 28 days compressive strength of the slag and cement blend by 14.7% and 20.1% respectively. This can be explained by the pozzolanic effect caused by the free lime in the thermally treated RCF and the quick rehydration of the dehydrated cement paste.

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