



Physio-chemical reactions in recycle aggregate concrete

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ABSTRACT

Concrete waste constitutes the major proportion of construction waste at about 50% of the total waste generated. An effective way to reduce concrete waste is to reuse it as recycled aggregate (RA) for the production of recycled aggregate concrete (RAC). This paper studies the physio-chemical reactions of cement paste around aggregate for normal aggregate concrete (NAC) and RAC mixed with normal mixing approach (NMA) and two-stage mixing approach (TSMA) by differential scanning calorimetry (DSC) and scanning electron microscopy (SEM). Four kinds of physio-chemical reactions have been recorded from the concrete samples, including the dehydration of $C_3S_2H_3$, iron-substituted ettringite, dehydroxylation of CH and development of C_6S_3H at about 90 °C, 135 °C, 441 °C and 570 °C, respectively. From the DSC results, it is confirmed that the concrete samples with RA substitution have generated less amount of strength enhancement chemical products when compared to those without RA substitution. However, the results from the TSMA are found improving the RAC quality. The pre-mix procedure of the TSMA can effectively develop some strength enhancing chemical products including, $C_3S_2H_3$, ettringite, CH and C_6S_3H , which shows that RAC made from the TSMA can improve the hydration processes.

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1. Introduction

Concrete waste constitutes the major proportion of waste at about fifty percent of the total waste generated [1]. It is possible to recycle this waste by reusing them in other construction applications. An effective method would be the use of RA in the production of RAC. RA consists of stone particles attached with some old cement mortar generated in the process of crushing the demolition concrete waste while RAC is concrete, in which RA is added along with other natural ingredients.

Use of RAC fulfils three “green” requirements as set out by the World Environmental Organization: (i) it can recycle and reduce natural resources and energy consumption; (ii) it will not affect the environment; and (iii) it can maintain sustainable development. Therefore, RAC is “green” concrete. Although reuse of RA reduces the consumption of limited resources and thereby saves costs, they have some shortcomings; for examples, weak interfacial behaviour between aggregate and cement paste, and high portions of cement mortar attached that lower its quality [2–12]. To facilitate the use of RA, it is vital to identify some ways to overcome these shortcomings.

Therefore, this paper focuses on the following objectives:

- To develop a new mixing approach, TSMA, for improving RAC performance;
- To investigate the physio-chemical reactions in RAC by DSC and SEM; and
- To identify benefits possibly gained from the use of the TSMA.

2. Obstacles in the use of recycled aggregate

Although it is environmentally beneficial to use RA, the current legislation and experience are not able to support and encourage recycling demolition concrete waste [13,7]. Some technical problems, including weak interfacial transition zone between cement paste and aggregate, porosity and traverse cracks within demolition concrete, high level of sulphate and chloride contents, impurity, cement attached on RA, poor grading, and high variations in quality, render the use of RA difficult [2–5,7–12,14–27].

Since aggregate generally occupies about sixty to seventy percent of the total volume of concrete, its selection and proportioning should be given careful attention. In addition to their use as economical filler, aggregate generally provides concrete with better dimensional stability and wear resistance. In choosing aggregate for particular concrete applications, attention should be given to the three general requirements: economy of the mixture, potential strength of the hardened mass and probable durability of the concrete structure. Since RA has large open porosity, concrete pro-

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Table 1
Composition of minerals in Portland cement [40]

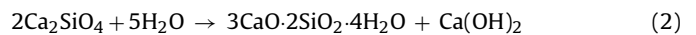
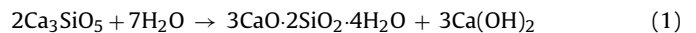
Mineral	Formula	% by weight CO ₂	SO ₃	CaO	Al ₂ O ₃
Gypsum	CaSO ₄ ·2H ₂ O	–	46.5	32.6	–
Ettringite	Ca ₆ Al ₂ (SO ₄) ₃ (OH) ₁₂ ·26H ₂ O	–	19.1	26.8	8.1
Monosulfaluminate	Ca ₄ Al ₂ (SO ₄)(OH) ₁₂ ·6H ₂ O	–	12.9	36.0	16.4
Calcite	CaCO ₃	44.0	–	56.0	–
Monocarboaluminate	Ca ₄ Al ₂ (CO ₃)(OH) ₁₂ ·5H ₂ O	7.7	–	39.5	17.9
Hemicarboaluminate	Ca ₄ Al ₂ (CO ₃) _{0.5} (OH) ₁₃ ·5.5H ₂ O	3.9	–	39.7	18.1
Hydroxyl-AFm	Ca ₄ Al ₂ (OH) ₁₂ ·7H ₂ O	–	–	40.0	18.2
Portlandite	Ca(OH) ₂	–	–	75.7	–

duced from it would be more subject to deformation and less resistant to mechanical abrasion. Density, compressive strength, modulus of elasticity, flexural strength, tensile strength, splitting tensile strength, bonding strength and shrinkage can deteriorate up to 10%, 86.4%, 50%, 16%, 6%, 50.7%, 26% and 53.4%, respectively, for RAC in comparison with NAC [28–39].

3. Cement and aggregate chemistry

At the micro-structural level, hardened cement paste (HCP) is an intimate but inhomogeneous mixture of a variety of crystalline and quasi-crystalline phases and pores of different sizes and shapes. Table 1 shows the composition of the most common minerals in Portland cement. Four major compounds: tricalcium silicate [3CaO·SiO₂ or C₃S], dicalcium silicate [2CaO·SiO₂ or C₂S], tricalcium aluminate [3CaO·Al₂O₃ or C₃A] and tetracalcium aluminoferrite [4CaO·Al₂O₃·Fe₂O₃ or C₄AF] are found in ordinary Portland cement [40–42]. In concrete, the major strength contributor is calcium silicate hydrate [CaO·SiO₂·H₂O, abbreviated as CSH], the principal hydration product, which is a highly disordered crystalline material of variable composition. Upon the addition of water, C₃S rapidly reacts to release calcium ions, hydroxide ions, and a large amount of heat. The pH value rises quickly to greater than 12 because of the release of alkaline hydroxide (OH⁻) ions. This initial hydrolysis slows down quickly after it starts, resulting in a decrease in heat evolved. The reaction continues slowly and produces calcium and hydroxide ions, until the system becomes saturated. Once this occurs, the calcium hydroxide [Ca(OH)₂, abbreviated as CH] starts to crystallize. Simultaneously, CSH begins to form. Ions precipitate out of solution, which accelerates the dispersion of C₃S to calcium and hydroxide ions. The evolution of heat is then dramatically increased. The formations of CH and CSH crystals provide ‘seeds’ upon which more CSH can form. The CSH crystals grow thicker making it more difficult for water molecules to reach the unhy-

drated C₃S. The speed of the reaction is now controlled by the rate at which water molecules diffuse through the CSH coating. This coating thickens over time, causing the production of CSH to become slower and slower. The molecular structure of CSH is layered and provides for a very high internal porosity. The process of the hydration of C₃S is given in Eq. (1) [43]. C₂S also affects the strength of concrete through its hydration. C₂S reacts with water in a similar manner of C₃S, but much more slowly. The heat released is less than that generated by the hydration of C₃S because the C₂S is much less reactive. The process of the hydration of C₂S is given in Eq. (2) [43]:



In contrast to CSH, Ca(OH)₂ [CH], also known as Portlandite, is highly crystalline and has a fixed composition, which comprises more than 20% of the hydration products in a fully cured cement paste [44]. CH appears as thin hexagonal platelets, often layered, typically tens of μm across. With continued hydration, they grow massively, lose their hexagonal outline, and encapsulate other regions of the paste [29]. Massive blocks of CH crystals can be easily identified in mature pastes. Unhydrated residues of clinker grains, which are crystalline in nature, are present even in well-hydrated systems. They are produced by the hydration of the silicate phases, C₃S, C₂S, and free lime [CaO] as shown in Eqs. (3)–(5) [44,45]. It can be seen from Eqs. (3) and (4) that the weight for the hydration of C₃S (Eq. (3)) is three times the amount of CH as does the hydration of C₂S (Eq. (4)). Thus the ratio of these two phases will affect the amount of CH formed.

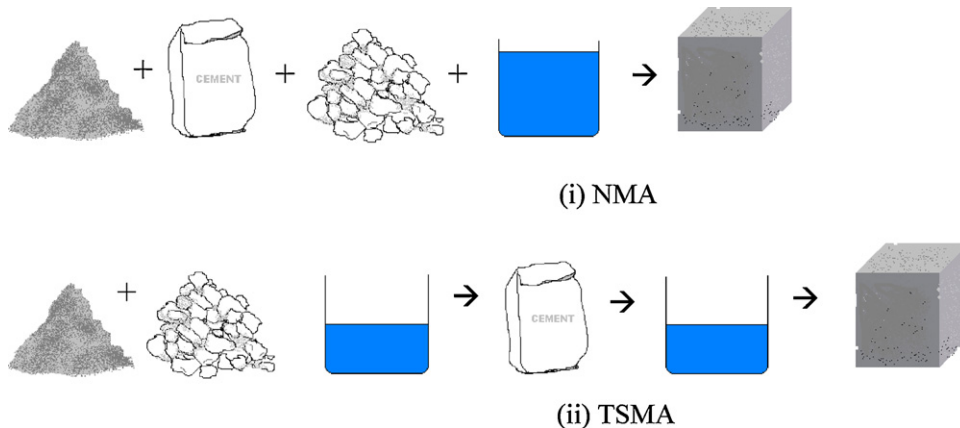
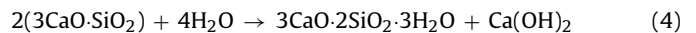
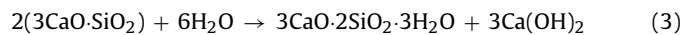


Fig. 1. Mixing procedures of (i) normal mixing approach and (ii) two-stage mixing approach.

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