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Review Paper

State of Art Reviews on Physico-chemical Properties of Waste Concrete Aggregate from Construction and Demolition Waste

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A B S T R A C T

Numbers of waste concrete have generated from construction and demolition waste (CDW) threaten environmental and human health due to the illegal dumping practices in several countries. Recently, the recycling of waste concrete has demonstrated the ability to reduce dependency on a natural resource in producing building materials as well as reducing carbon footprint in the concrete manufacturing process. The objective is to determine the limitation factors of Waste Concrete Aggregate (WCA) as a replacement for virgin concrete aggregate. Analysis by X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), leaching, and sulphate tests were used to identify the physicochemical characteristics of WGA. Results showed WCA has high water absorption, expansion of Alkali-Silicate Reaction (ASR), low adhesive strength between aggregate and cement, leachability, and high soluble sulphate. CaO, Al_2O_3, SiO_2, SO_4^{2-}, Cr_2O_3, SrO, and Al_2O_3 were the main chemical components consisting of WCA. The leachability of Ca, Zn, and Cr in WCA was pH-dependent. High soluble sulphate content in WCA determined the extension formation of micro-crack in WCA due to extensively recrystallizing the Delay Ettringite Formation (DEF) in WCA. The formation of micro-crack, ASR, and low adhesive strength between aggregate and cement insides of WCA significantly affect the durability of recycled products in building structures. High water absorption and leachability of WCA enhanced the release of heavy metals in soil. Therefore, these limiting factors in WCA were necessarily treated before being utilized as a part of the recycled product.

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INTRODUCTION

Construction and demolition waste (CDW) is a solid waste generated from any construction and demolition activities due to the improvement, preparatory, repair or alternation work. These activities included civil and building construction, renovation, and demolition (site clearance, roadwork, land excavation and formation) [1]. It is also categorised as inert solid waste and a complete loss of physical waste from construction sites [2, 3]. Nowadays, the construction industry plays a vital role in economic growth to improve the quality of life by providing necessary infrastructures such as roads, housing, commercial development and other facilities. In Malaysia, the government has allocated 5,555 projects for the development sector by improving the residential, non-residential building projects, social amenities and infrastructure projects [4]. Therefore, high demand in construction activities has generated a high volume of CDW.

The generation of CDW is usually due to the problem with planning, material, human and the environment such as frequently change in design, low quality of materials [5], worker mistake [6–8], weak ability on-site management [9] and bad weather [8]. High project development on housing, infrastructures or commercial buildings has generated a high volume of CDW [10]. High transportation costs and distance of location projects are among the reasons to select illegal dumping as a disposal practice besides conflict in carbon dioxide emission. Thus, providing a systematic and efficient waste management service such as re-using or re-cycling

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construction waste materials is required to minimise the amount of CDW being dumped at illegal sites or landfills and the carbon footprint of construction industry.

To address these challenges, this study purposely determines the limitation factors of Waste Concrete Aggregate (WCA) as a major CDW to replace the usage of virgin concrete aggregate in the concrete manufacturing process.

Waste concrete as major CDW

There are many types of physical waste generated from CDW e.g. concrete, ceramic, metal, plastic, brick, tile, asphalt, gypsum, paper, glass, sand and wood [11–13]. Based on previous findings, it was found that concrete dominated the physical waste generated from CDW [11, 12].

Moreover, Construction Industry Development Board (CIDB) has claimed concrete debris as a major component generated by the construction industry [14] Therefore, the introduction of the Industrial Building System (IBS) by CIDB as an alternative to re-enforce the commitment of the construction industry toward sustainable development, in order to implement zero waste concept in the construction industry.

Characteristics of concrete

Concrete was generally used as a construction material in structural applications [15]. Concrete is considered the main waste generated among CDW due to the high demand for major infrastructure projects, housing and commercial development [16]. Cement, sand and coarse aggregate are the main materials for the production of concrete. Therefore, crushed waste concrete aggregate potentially has to vary the portion of cement attached with sand and/or coarse aggregate. Hence, the variation amount of the attached cement paste requires to be analysed before conducting a treatment on crushed waste concrete which influence the deterioration degree of concrete [17].

RECYCLING CDW OVERCOME CARBON FOOTPRINT IN CONSTRUCTION INDUSTRY

Many researchers attempted to create various types of CDW as recycled material as it is applicable to numerous functions such as pedestrian blocks [14], unbound structure layer of road [11], mortar [18] and concrete [19]. Besides waste concrete, there are many types of CDW potentially to be recycled, for instance, bricks [20, 21] plastic [22], ceramic [23] and glasses [24–26].

The production of the cement and concrete aggregate faces a few challenges, particularly on CO_2 emission and somewhat costly in energy supply [27]. The energy supply in construction manufacturing emits lots of CO_2 from the activities of transportation due to the usage of diesel, use of water and explosive agent, casting and laying process, and electricity [28]. The consequence of CO_2 emission from this industry influences the carbon footprint resulting from the greenhouse effect in the concrete production industry. Owing to those factors, many studies have been directed to investigate various types of CDW to produce high-performance recycled products that simultaneously reduces the dependency on cement and natural resource as raw material. CO_2 emissions gradually decrease by increasing the percentage of recycled aggregate in concrete mixtures [28].

Replacement materials such as wood ash, plastic, glass, ceramic and brick have similarities in certain physical and chemical features of cement and concrete aggregate. This replacement material has fine particle size, low water absorption, low unit weight and specific gravity [29]. Besides, rich carbon, silica, alumina, portlandite and lime, are relative to neat cement [30]. However, several factors have limited the capability of these replacement materials to be recycled, although the presence of pozzolana components (Table 1).

These limiting factors have caused high water absorption, crack formation, expansion of alkali silicate reaction (ASR) and low adhesive strength between replacement materials, cement and /or aggregate. These conditions led to air-entraining action and water infiltration in void spaces, which eventually promoted an extensive ASR and micro-crack formation. Furthermore, these replacement materials depend on a super-plasticiser to overcome the drawback properties where it could enhance the adhesive strength at the Interfacial Transition Zone (ITZ), producing high compressive strength of recycled products [23, 28].

CHARACTERISTICS AND EFFECTS OF USING WASTE CONCRETE AGGREGATE (WCA) FROM CDW

Waste concrete aggregate (WCA) is a complete loss of physical solid waste removed from construction sites to disposal sites [3]. Among the generation factors for such solid waste are carelessness, over-ordering and over-filling the container of lifting equipment while concrete casting [13]. This poor management by an unskilled workforce causes lower productivity and workmanship at construction sites [31]. Subsequently, WCA is highly generated compared to other types of CDW [12].

Physical characteristics

Density is one of the fundamental parameters and determines concrete mixes design which directly controls other concrete properties. It is also the most common method to characterize the aggregates. The low density of WCA is related to a high content of attached cement paste [17]. The reasons are the porosity and less density of attached cement paste adhered onto the surface of WCA which simultaneously leads to the low density of WCA

[32]. The recycling procedure of WCA had discussed by Silva et al. [33] that may affect the density of WCA. Crushing the concrete rubble into smaller sizes is the first step in the recycling procedure.

The recycling procedure for waste concrete requires a pass-through primary and secondary stage of the crushing process [34–36]. A jaw crusher is typically used in the primary stage, while, a cone crusher and impact crusher are used during the secondary crushing stage to produce rounder and less sharp particles of fine WCA. The number of crushing stages influences the density of WCA, of which more crushing stages will cause a lower density of WCA [28]. This scenario is due to the cumulative breaking up of adhered cement paste on the surface of the WCA. Therefore, Ai et al. [37] has suggested that the crushing stages should not be too few or too many, otherwise, the produced fine WCA has low density due to the high amount of attached cement paste [38]. Thus, the density is expected to be low due to the accumulation of attached cement paste in fine WCA.

Although these materials are potentially useful as replacements for cement or concrete aggregate, these limiting factors have restrained the value-added of these materials in the production of recycled concrete and mortar. Several works have reported the effect of using these materials on long-term durability, compressive strength and toxic chemicals they may possess [24, 39, 40].

IBS system has shown that the major CDW is waste concrete [12]. Therefore, the use of waste concrete as a replacement material for concrete aggregate portions could reduce the amount of waste generation, of which sustainable development in the construction industry could further be achieved. Also, many studies have demonstrated that recycled waste concrete that has been used as a replacement material has no adverse effect on the mechanical strength of the recycled product when approximately 30% of waste concrete was mixed with coarse aggregate [41].

For recycling purposes, a total construction budget has been saved up to 2.5 % when a recycling approach on CDW was introduced [42]. Besides, the dependency on natural resources can be reduced and subsequently, the cost of raw materials also can be reduced. In addition, the production of aggregate and cement at a quarry requires acid washing to remove any unwanted elements and a frequent washing surface run-off of silt, sand or gravel in drainage pipes may lead to the blockage. Thus, the production of aggregate and cement at the quarry does not only cause water wastage but also could harm the biotic life due to the toxic chemical utilisation [43]. Moreover, excessive energy consumption (up to 40% of the total energy needed) for the production and transportation of aggregate and cement is another reason why a recycling approach should be considered [44].

The construction industry has widely utilised the recycling approach. For example, approximately 30 million tonnes of recycled concrete aggregate were utilised in the UK [45] While, In the USA, Federal Highway Administration has utilised CDW as recycled concrete and pavement [46]. Recycled concrete aggregate also can be used for the production of lightweight building materials as well as high-strength concrete [47].

Table 1. Limitations of different types of CDW for cement and concrete aggregate replacement

Replacement Material	Limitation	References
Marble powder	Irregular shape, fineness particle size (< 7µm) resulted in demanded water for cement hydration	[23, 28]
Wood ash	High combustible organic content caused water demand for cement hydration	[30]
	Prolong setting time due to difficulty to dilution for cement hydration	[48]
	The late pozzolanic reaction caused retardation of cement hydration	[49]
	Act as a filler, not binder material	[30]
	Increased replacement material percent reduces compressive strength	[28]
Plastic	Hydrophobic, sharper edge, angular size, slippery surface texture caused difficulty for cement hydration	
	High total surface area caused high water absorption	
	Short fibers acted as bridge-action of crack cause post-cracking on the specimen	[39, 50–52]
	Low adhesive strength	
	Increased replacement portion reduced compressive strength Low adhesive strength results in low compressive strength	
Glass	ASR reaction between high silicate of glass and high alkali of aggregate	
	Irregularity surface, smooth and sharper edge of particle	[24, 25, 39]
	Low adhesive strength	
	Micro-crack during crushing process lead ASR expansion	
Ceramic	Required huge amount of super-plasticizer	[21]
Brick	High water absorption due to high porosity	
	Angular shape caused difficulty for cement hydration	[22]
	Compressive strength not affected by percent of replacement ratio	

Generally, low-density WCA has an impact on mechanical strength [33, 53, 54]. A high amount of cement is required due to the low particles' mass of WCA to occupy the void spaces of recycled product specimens [17]. Previous researchers have demonstrated that the mechanical strength of different concrete mixes decreased when saturated surface dry density decreased [55]. It can be concluded that the mechanical strength is influenced by the density of aggregates. Meanwhile, Elzokra and colleagues [57] highlighted that concrete with a higher amount of attached cement paste (49.4%) tends to have lower mechanical strength i.e. 45 MPa compared to concrete with a lower cement paste (36.3%), of which the strength was 56 MPa. Thus, the amount of attached cement paste onto WCA influences its density which simultaneously affects the mechanical strength of the concrete [58].

Water absorption is another parameter to be considered when using WCA as similar factors as those designated for density [33]. The water absorption of an aggregate is directly related to its porosity which is highly dependent on the total amount of attached cement paste [54, 60]. The above statement is also supported by de-Brito and Saikia who stated that WCA has a higher water absorption value than that of natural aggregate due to the presence of attached cement paste [32]. As mentioned earlier, the more the crushing stages, the higher the amount of attached cement paste. Thus, the presence of attached cement paste with high porosity causes a higher amount of water to be absorbed by WCA.

High water absorption in WCA influences the concrete mixing process. It causes more water to be consumed which affects the water/cement ratio and eventually gives impacts the workability and the hardened process of fresh concrete [25]. Furthermore, excessive water leads to the formation of a thin layer of cement slurry on the surface of WCA which permeates into porous old cement mortar, micro-crack and voids [59]. Although cement slurry develops a strong ITZ between cement paste and WCA, but enhances the deterioration of concrete following the formation of ettringite, portlandite and calcium silicate hydrate (C-S-H).

Attached cement paste onto the WCA surface was technically impossible to be removed from the aggregate due to the cost and technical aspects [32]. Therefore, concrete mixes design requires additive stages which are pre-soaking, to prevent excessive suction of mixing water during the mixing process [61]. Pre-saturated of WCA followed with 30 min air-dried has demonstrated better mechanical performance of recycled concrete as compared to the oven-dry alone [62]. Angulo and colleagues showed that soaking WCA with water has a great effect on water absorption value i.e. 17% reduction from the initial value [63]. Therefore, pre-treatment with soaking and air-dried procedures could improve water absorption of WCA.

Mineralogical and chemical characteristics

Solid waste of CDW is usually dumped at disposal sites without any segregation process and it is important to determine the mineralogical characteristic of WCA due to the possible hazardous minerals (amianthus) present in asbestos. Moreover, the mineralogical characteristics of WCA influence the procedure of recycled concrete products such as water/cement (w/c) ratio and curing day, to achieve an equal performance as ordinary concrete [45]. In the laboratory, the X-ray diffractometry (XRD) technique is commonly to detect types of minerals constituted in WCA.

Generally, minerals such as calcite, quartz, ettringite and portlandite are commonly detected in WCA [64, 65]. Quartz is present in natural rock, while, calcite is from cement [66]. WCA tends to have low portlandite as compared to natural aggregate due to the light pozzolanic effect [64]. Low portlandite in WCA causes an un-stable of ettringite and subsequently increases the solubility of sulphate ion in pore water occupied in void spaces of concrete. Besides, high calcite content indicated carbonated WCA due to the rich CaO [65].

Although density and water absorption are vital parameters that control the workability of concrete and mortar, inorganic elements within WCA should also need to be concerned. Many researchers have pointed out that the CDW has a feasibility threat to the environment and human health [67]. Nowadays, recycled concrete and mortar are utilised in road construction and building structures. However, during their service life span, environmental impacts from rain, surface water and groundwater are potentially in contact with existing inorganic elements from the WCA. The environmental impact does not rely on the total content of pollutants but depends on the amount of the pollutants able to be dissolved by water and subsequently leaching out from the medium [68, 69]. This phenomenon finally pollutes the surface or groundwater. Thus, potential inorganic elements leaching out from the waste concrete and solubility of each element are among crucial parts to assess environmental impact. Furthermore, the EU commission had claimed that CDW is one of the main waste streams to be dumped in landfills [70].

Inorganic elements in WCA are examined by X-ray fluorescence (XRF) spectrometry. Since the environmental impact is correlated with ions that leached out from WCA, therefore, leachability of ions is related to the chemical element of WCA [71]. Previous research on pH-dependent batch leaching tests to determine the leaching behaviour of chemical elements from WCA. This method used 10 ± 0.3 ml/mg as liquid to solid ratio for 48 hours agitation period with deionized water as the extraction medium [72].

XRF analysis and leaching tests from previous studies have shown that calcium oxide (CaO), aluminium oxide (Al_2O_3) and silicon dioxide (SiO_2) are the main chemical elements leached out from concrete aggregate [64]. Few elements such as SO_4^{2-}, Cr_2O_3 and SrO are only detected as trace elements. While, abundant with the element of Al_2O_3 in waste concrete due to the clay-based minerals, which are the main element of attached cement [18].

Leachability

A serious matter that needs to be considered concerning the use of WCA in the construction industry is it may contain leachable pollutants (trace inorganic elements) to human health and the environment [73, 74]. Leached trace elements such as lead, copper, cadmium and zinc in urban runoff caused accumulation in buildings, particulates in vehicle brakes and air pollution [75]. The presence of sulphate element in quartz has a cathartic effect on human health when its presence is in an excessive amount [76]. Leaching behaviour by testing the materials under pH-controlled conditions has considerably increased following the fact that pH is one of the major parameters regulating the release of elements from the solid phase into the solution. The test can be used to identify any changes in leaching behaviour. The long-term potential risks are generally to the elements of Mo, V, As, Cr, B and Sb, in which, the leachability of these elements is high at mild alkaline to neutral pH. Furthermore, these elements are the most frequently found in cement-based products after long term exposure under environmental condition.

Most inorganic elements in WCA such as Ca, Zn and Cr are pH-dependent with only Se showing no pH-dependency behaviour for it could be leached out from WCA [72]. Leaching trends for each element are different and depend on the solubility of minerals or the solubility of metal hydroxide [71]. For example, low pH of the solution would lead to an unstable stage of calcite and simultaneously causes a high concentration of Ca in leachate [72]. While higher pH of the solution (more than 11) would cause dissolution of Fe-monosulphate (FeS) and amorphous iron(III) hydroxide ($Fe(OH)_3$) which further causes the concentration of Fe to incline [72].

Soluble sulphate content

In soil, sulphates are present in the form of calcium, magnesium, sodium and potassium [77]. Ammonium sulphate, for example, is frequently found in agricultural soil and water. In WCA, sulphate is commonly present in attached cement paste and concrete aggregate clinker [78]. However, Scanning Electron Microscope (SEM) analysis has proved that sulphate was found in ettringite minerals as a part of attached cement paste components [79]. Sulphate from aggregate clinker reacted spontaneously with anhydrous calcium aluminate from cement particularly for cement hydration [80]. However, enhancement of sulphate content in concrete has caused micro-crack formation at ITZ that slowly increases the crack length by moving outward the concrete surface (Figure 1) [80]. This micro-crack causes the loss of mass from aggregate and/or cement, which subsequently reduces the mechanical strength performance of concrete.

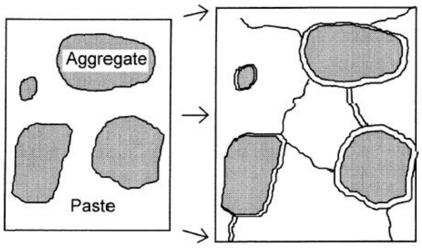

Figure 1. Micro-crack [80]

ETTRINGITE AS A SOURCE OF MICRO-CRACK IN CONCRETE AND MORTAR

Ettringite or calcium sulfoaluminate ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) is a needle-like crystal which normally found in Portland cement concretes (Figure 2) [81]. This mineral is at first, a necessary and beneficial component that controls the hardening process. Gypsum, as a source of calcium sulphate is purposely added to Portland cement to regulate early hydration reactions to avoid flash setting and reduce drying shrinkage. It also improves strength development. Gypsum and other sulphate compounds react with calcium aluminate in the cement, forming ettringite within the first few hours following the water addition (Equation (1)). At this stage, ettringite is uniformly and discretely dispersed throughout the cement paste at a very low level. Uniform distribution of ettringite does not affect any expansion on concrete or cement mortar [82]. Ettringite formed at early ages is often referred to as "primary ettringite" or early ettringite formation (EEF).

$$3\,CaO \cdot Al_2O_3 + 3\,(CaSO_4 \cdot 2H_2O) + 26\,H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O \quad (1)$$

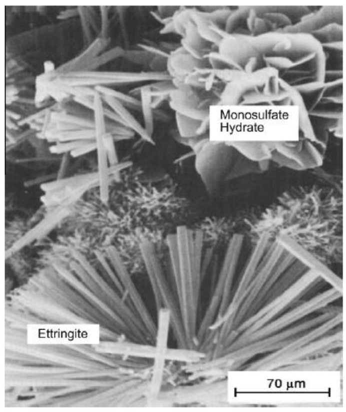

Figure 2. The shape of ettringite and monosulphate as observed by [83]

Delayed ettringite formation (DEF) in WCA

Delayed ettringite formation (DEF) is a concrete expansion and cracking associated with the reformation of the mineral ettringite, a normal product of early cement hydration (EEF). For so many years, it has been widely known that concrete with long exposure to water will cause EEF to slowly dissolve and reform in any available voids or microcracks [82]. This newly reformation of ettringite is called DEF. DEF takes months or years to fully grow in rigid hardened WCA. Compared to EEF, the expansion of DEF is heterogeneous, massive and non-uniform [82]. DEF forms in void spaces from the surface and it slowly expands into the concrete or mortar. Recrystallization of DEF increases the crystal volume in void spaces, which finally triggers the swell pressure and causes limited void spaces [80]. Furthermore, recrystallization of DEF often elongated along crystallographic axis and creates a new phase in the void space. This process causes the pore solution to be supersaturated with sulphate ions [84].

The expansion of DEF, on the other hand, has a detrimental effect on the compressive strength of concrete and mortar due to the reduction of their elasticity and strength [85]. The formation of ettringite and the expansion of DEF are poorly documented but contributing factors such as humid environment (continuously expose to rain and sun), the temperature in the range of 25℃ to 40℃, carbonation process, the presence of mineral calcite and portlandite, oxyanions (Cr, As, Se and Sr) in pore solution and weak bond between aggregate and cement led to the formation of recrystallization DEF in WCA structure have been reported [82].

Roles of sulphate in DEF

The presence of sulphate in concrete is for concrete resistance towards corrosion and fast setting purpose during the production of cement. However, sulphate becomes problematic for its presence could lead to the formation of DEF, which subsequently reduces the concrete strength. The formation of DEF by sulphate in void space gives an impact on the durability of concrete and cement mortar, which is referred to as compressive strength [79, 86]. Low compressive strength demonstrates a high volume of void spaces due to the wider ITZ with micro-crack [87]. Thus, concrete with decreased compressive strength demonstrates the high expansion of DEF with high sulphate content in WCA.

Reduction of sulphate ions from DEF is the most suitable method to reuse WCA since many studies have reported that sulphate ion is able to be reduced by controlling a chemical composition in WCA [88]. Yet, none of the research emphasises sulphate reduction in WCA as a remediation treatment before being utilised as a part of the recycled product.

CONCLUSION

Recycling WCA from CDW enables overcoming issues of illegal dumping and reduces carbon footprint in the concrete manufacturing process. Therefore, important to examine the physico-chemical characteristics of WCA due to the capability of replacement from natural resource concrete aggregate, the durability of a recycled concrete aggregate and potential threat to the environment as well as human health. CaO, Al_2O_3, SiO_2, SO_4^{2-}, Cr_2O_3, SrO and Al_2O_3 were the main components consisting of WCA. Leachability of Ca, Zn and Cr in WCA were pH-dependent. Soluble sulphate content was the main parameter determination of the formation of micro-crack in WCA. The presence of soluble sulphate content extensively recrystallized the Delay Ettringite Formation (DEF) of WCA. Therefore, necessarily remediate the limiting factors of physicochemical properties WCA before recycling process.

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Persian Abstract

چکیده

تعداد ضایعات بتن تولید شده از زباله‌های ساخت و ساز و تخریب (CDW) به دلیل شیوه‌های تخلیه غیرقانونی در چندین کشور، سلامت محیط زیست و انسان را تهدید می‌کند. اخیراً بازیافت بتن ضایعاتی توانایی کاهش وابستگی به منابع طبیعی در تولید مصالح ساختمانی و همچنین کاهش ردپای کربن در فرآیند تولید بتن را نشان داده است. هدف تعیین عوامل محدودکننده سنگدانه بتن زباله (WCA) به عنوان جایگزینی برای سنگدانه بتن بکر است. تجزیه و تحلیل با پراش پرتو ایکس (XRD)، فلورسانس اشعه ایکس (XRF)، لیچینگ و آزمایش‌های سولفات برای شناسایی ویژگی‌های فیزیکوشیمیایی WGA استفاده شد. نتایج نشان داد که WCA دارای جذب آب بالا، انبساط واکنش قلیایی سیلیکات (ASR)، استحکام چسبندگی پایین بین سنگدانه و سیمان، قابلیت شستشو و سولفات محلول بالا است. CaO، Al_2O_3، SiO_2، SO_4^{2-}، Cr_2O_3، SrO و Al_2O_3 اجزای شیمیایی اصلی متشکل از WCA بودند. قابلیت شستشوی کلسیم، روی و کروم در WCA وابسته به pH بود. محتوای سولفات محلول بالا در WCA به دلیل تبلور مجدد گسترده تشکیل Etringite تاخیری (DEF) در WCA، تشکیل گسترش میکرو ترک را در WCA تعیین کرد. تشکیل ریز ترک، ASR و استحکام چسبندگی کم بین سنگدانه و داخل سیمان WCA به طور قابل توجهی بر دوام محصولات بازیافتی در سازه های ساختمانی تأثیر می‌گذارد. جذب آب بالا و قابلیت شستشوی WCA باعث افزایش رهاسازی فلزات سنگین در خاک شد. بنابراین، این عوامل محدودکننده در WCA لزوماً قبل از اینکه به عنوان بخشی از محصول بازیافتی مورد استفاده قرار گیرند، درمان شدند.