

The Utilization of Recycled Materials for Concrete and Cement Production- A Review

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Abstract. The utilization of recycled materials is one of the seven principles of sustainable construction. These principles based on the efficient use of resources were defined by the International Council of Building in 1994. Recycled materials such as recycled concrete aggregate or recycled brick aggregate from construction and demolition waste, waste glass from municipal waste or recycled waste gypsum from gypsum boards are able to use as replacement of primary raw materials in cement and concrete production. Concrete and cement production totally depends on the natural resources. The world production of concrete has been twelve times increased during last six decades. Nowadays, nearly one ton of concrete is produced each year for every human being in the world on average. On one hand, the use of recycled materials in cement and concrete production helps to reduce raw materials and urban land occupation. However, on the other hand, the recycled materials used as partial replacement of raw materials influence properties of final product. This paper reviews the different uses of recycled materials in cement and concrete production and the effect of the properties of these materials to the cement and concrete quality.

Keywords: Construction and demolition waste, Recycled concrete aggregate, Recycled brick aggregate, Waste glass, Recycled cement powder, Fine recycled aggregate

1. Introduction

Concrete is the most widely used construction material that is caused by its excellent mechanical and durability properties. Nearly one ton of concrete is produced for every human being in the world each year [1], which means almost ten billion tons of concrete annually. Concrete and concrete structures, which are used for buildings, bridges, dams etc. have a large impact on the environment, due to their enormous production and utilization. The most important environmental impacts of concrete production are progressive depletion of natural resources, high consumption of energy, large amount of emissions of greenhouse gasses and large amount of construction and demolition waste production [2]. The consumption of energy is mainly connected with cement production which accounts for 83% of total energy use in the production of non-metallic minerals [3] and represents around 90% of total embodied energy of concrete [4]. Furthermore, the emissions of greenhouse gasses which are responsible for climate change originate mainly from cement production and emissions of SO_x which is responsible for acidification mainly originates from the concrete production [4]. Aggregate represents only 13% to 20% of total CO₂ emissions of concrete in contrast with cement production which is responsible for 74 % to 81 % of total CO₂ emissions of concrete [5] and the cement industry



accounts for approximately 5-7 % of total world CO₂ emissions [2], [6]. Finally, the large amount of construction and demolition waste (CDW) is produced. As the result of increasing construction industry, widespread urbanization and the economic condition, the old constructions are being demolished to build new structures. Due to these activities, the huge amount of the CDW is generated all over the world. The amount of CDW represents 25% -30% [7] of the overall waste generation and 850 million tons were generated in EU per year [8]. The CDW originates from the construction, renovation and demolition of buildings, bridges, roads and other structures. The CDW typically contains inert materials such as concrete, bricks, plasters etc. and also hazardous particulars such as asbestos, particulate matters etc. [9]. Inert waste is considered to have a priority to be recycled according to the EU Waste Strategy [10]. The waste concrete accounts for about 45% of construction waste, which is the highest percentage representation [11].

The concrete production is totally dependent on primary raw materials such as natural sands, natural gravel, cement and water. The reduction of environmental impacts of cement and concrete production could be occurred by utilization of waste materials in building industry. One of the main assumption for the use of recycled CDW is selective demolition, which means very thorough sorting of materials during demolition process [5]. This could lead to the good quality input materials for recycling process and subsequently to the secondary raw materials, which is possible to use as replacement of primary raw materials for new applications.

2. The possibilities of natural aggregate replacement in concrete production

High and constantly and rapidly increasing concrete production causes still growing natural resources depletion and amount of inert CDW. It was estimated that three billion tons of aggregate were consumed in European Union [12]. The use of recycled aggregate (RA) as partial or full replacement for natural aggregate in concrete structures belongs to one of the most effective approaches for recycled CDW utilization.

The research of the replacement of natural gravel by coarse recycled aggregate has become very complex over the last four decades. Recycled aggregate characteristics and their influence to concrete properties have been investigated during these decades. Mechanical, physical and durability properties of recycled aggregate concrete were examined and describes in many studies. The use of fine RA replacement as partial or full replacement of natural sand is mainly complicated by the higher mortar and impurity contents of the fine RA as compared to coarse RA [13]. This is one of the main reason that the replacement of sand in concrete mixture by secondary raw materials has not been defined in Standards yet. Although, the sand extraction from seaside has high environmental impact such as increasing seaside erosion, changing wave behavior, local fauna and flora ecosystems and other environmental aspects. The sand extraction from riverbed has negative impact to local ecosystems [14].

Recycled concrete aggregate (RCA), which contains more than 70% of concrete particles, is according to standards [15], [16] possible to use as partial replacement of coarse natural aggregate in certain applications (see Figure 1.). The use of recycled brick aggregate (RBA), which contain more than 50% of brick particles, fine RCA and RBA, originated from concrete or bricks CDW, and glass aggregate has not been defined as partial replacement of aggregate in concrete in Czech standards yet. As it was written before, the main assumption of high quality recycled materials, which are possible to use as partial replacement in new structural applications is sophisticated demolition and recycling process.



Figure 1. RCA from Czech recycling centre of fraction 63/120, 8/16, 4/8 and 0/4 mm

2.1. The utilization of recycled concrete aggregate (RCA) in concrete mixture

The possibilities of utilization of RCA are mainly connected with quality and properties of recycled aggregate. The main barriers in utilization of RCA are their high water absorption which negatively influence workability of fresh concrete and unwanted impurities which could degrade mechanical properties of concrete [13]. The water absorption of coarse RCA is between 0.5% and 14.75% which is up to twenty times higher in comparison with natural aggregate. The dry density of coarse RCA is generally lower than that natural gravel and ranges from 1900 to 2700 kg/m³ [13]. The water absorption of fine RCA is between 4.3% and 13.1% and the dry density of fine RCA ranges from 1900 to 2360 kg/m³ [17]. Higher water absorption and lower density of RCA is caused by old mortar attached on the surface of origin aggregate, due to that mortar is more porous and is less dense than the particles of aggregate [13].

2.1.1. The utilization of fine RCA in concrete mixture. The studies of utilization of fine RCA as partial or full replacement of sand show the main problems with its use such as higher water absorption due to high content of cement mortar and unwanted and undefined impurities. The water absorption of recycled aggregate concrete with partial replacement of sand and gravel of RCA is higher in comparison with conventional concrete. The main reason is high porosity of recycled concrete aggregates, which leads to mixes with higher w/c ratios, in order to achieve a constant workability [18]. On one hand, the fines content (particles finer than 75 µm) of aggregate has larger surface area, which leads to higher water consumption. On the other hand, the fines content would fill pores between larger particles for better aggregate skeleton of concrete mixture [19]. The particles size between 125 – 500 µm shows high content of cement mortar [14]. This could lead to the better mechanical and permeability properties of concrete. The maximal replacement rate of sand by fine RCA in concrete mixtures without significant effect to the mechanical properties is up to 30% [20]. However, in this study the laboratory prepared fine RCA was examined, which could show different results than fine RCA from CDW. The results of study where natural sand was replaced by fine RCA show decrease of compressive strength between 25% -30%, However, the mixtures with fine RCA contained less cement in this study. The results of compressive strength for replacement rate of sand by fine RCA was 25%, 50% and 75% were similar. The lowest compressive strength were examined for full replacement of fine fraction [21].

2.1.2. The utilization of coarse fraction of RCA in concrete mixture. Higher water absorption, the rougher surface and more irregular shape of RCA negatively influence the workability of fresh concrete [22]. Moreover, higher water absorption influence effective w/c ratio of concrete mixture [23]. Due to these findings, it is necessary to add more water to concrete former to attain a required workability. There are few ways how to reach it. One way is to pre-saturate the aggregate [23]–[25], further way is immersion of RCA 30 days in water [26], the third way is two-stage mixing approach [27]. The saturation level of the recycled aggregate could affect the mechanical properties of concrete, since at higher saturation levels the mechanical bonding between the cement paste and the recycled aggregate becomes weaker [28], [29].

The compressive strength of recycled aggregate concrete (RAC) is influenced by replacement rate of RCA and its quality and composition [30], [31]. Further, the decline of compressive strength depends on the presence of two interfacial transition zones, which is normally between aggregate and new cement mortar, but in RAC is also between attached old mortar and new cement mortar [27], [32], [33].

There were presented different maximal replacement rates of coarse aggregate in concrete by RCA without compressive strength degradation [13], [34], [35]. As a maximal replacement rate of natural gravel was stated 30% [13], [35] and 50% [13], [34]. The range of compressive strength decrease of concrete with full replacement of coarse natural aggregate by RCA is from 10% to 35% [2], [20]. The decline of compressive strength could be compensated by additional cement while maintaining the same amount of water. It is needed 8.3% of additional cement in concrete mixture with full replacement of natural aggregate [23]. Higher strength development of compressive strength of RAC after age 28 days is observed [20], [29]

The durability properties of concrete are an essential for its usage in structural applications. Concrete structures are very often exposed to the effect of thermal changes. The durability properties of concrete, especially freeze-thaw resistance and drying shrinkage could be negatively influenced by attached cement mortar and thereby higher porosity and water absorption of RCA. Drying shrinkage is higher for concrete containing RCA [21], [36], [37]. The water absorption by capillarity influence the freeze-thaw resistance of fine aggregate concrete. Higher capillary water absorption leads to worse freeze-thaw resistance [38]. The frost resistance of concrete is affected by its porosity, the water content in porous system and the environmental conditions. The frost resistance of RA can be assessed according to the method based on the change in the Los Angeles coefficient after 25 direct freezing–thawing cycles on saturated sample. Generally, the frost resistance of saturated RAC is not satisfying, and their use in structures exposed to severe climate is not recommended [39].

2.2. The utilization of recycled brick aggregate (RBA) in concrete mixture

The possibilities of utilization of RBA are mainly connected with properties and composition of recycled aggregate. The main barriers in utilization of RBA are their high water absorption which negatively influence workability of fresh concrete and unwanted impurities which could degrade mechanical properties of concrete [13]. The range of water absorption of coarse RBA is from 10.1% to 18.9%, which is up to twenty-five times higher in comparison with natural aggregate. The dry density of coarse RBA is generally lower than that natural gravel and ranges from 1800 to 2700 kg/m³ [40]–[43]. One of the main difference between sand and fine RBA is density and water absorption. The density of fine RBA mainly originated from crushed bricks was between 2000 and 2500 kg/m³ that is lower value in comparison with natural sand. The values of water absorption of fine RBA were measured between 12 and 15%, which is more than 10 times higher in comparison with natural sand [21], [40], [44].



Figure 2. The utilization of fine RBA in fine aggregate concrete mixture (50% replacement rate)



Figure 3. The utilization of coarse RBA in concrete mixture (up to 98% replacement rate)

2.2.1. The utilization of fine RBA in concrete mixture. The main characteristics of fine FBA responsible to the concrete properties were presented in many studies of utilization of fine RBA as partial or full replacement of sand [21], [40], [44]. High water absorption of fine RA causes worse workability of fresh concrete [21]. This finding have to be considered during mixture design and mixing, due to higher water absorption the additional water have to be calculated and add during mixing to concrete mixture to achieve the similar workability with conventional concrete mixture [44] or the aggregate were soaked into water for 24 hours before mixing [40]. The replacement ratios of fine natural aggregates by fine RBA were 25%, 50%, 75% and 100% [21], [40] and 20%, 50% and 100% [44]. As a coarse fraction was used natural aggregate. The compressive strength at age 28 days decreases with increasing replacement rate of sand [21], [40], [44]. The compressive strength between the age of 28 and 90 days increase for all mixtures containing fine RBA and the increase was higher in comparison with conventional concrete and with concrete containing fine RCA. Due to author's conclusions, the reason could be the silica and alumina contents in crushed bricks which could leads to the pozzolanic reactions [21]. The other reason could be lower w/c ratio of concrete mixtures with fine RA, due to non-compensation of high water absorption of RA and thereby lower effective w/c ratio. This assumption was proven by other studies where the w/c ratio was calculated according water absorption of RA. The results of these studies show no appreciable changes in the rate of strength development between the age of 28 and 90 days [40], [44]. The fine aggregate concrete mixture with 50 % replacement rate of sand by fine RBA is shown on Figure 2.

2.2.2. The utilization of coarse RBA in concrete mixture. The workability of fresh concrete with partial replacement of natural gravel by RBA is influence by its higher water absorption. The workability could be improved by pre-soaked RBA or adding additional water to concrete mixture during mixing process. Workability and effective w/c ratio influenced the compressive strength of concrete [45]. It was found that no significant changes in compressive strength of concrete containing coarse RBA with replacement rate 15%. The decline of compressive strength of concrete with containing coarse RBA replacement rate 30% was found [41]. The compressive strength of concrete with full replacement of coarse natural aggregate by RBA decreases up to 35% [40]. The concrete mixture with 0%, 66%, 75% and 98% replacement rate of gravel by coarse RBA is shown on Figure 3. Two shown concrete mixtures contain 46% and 58% of coarse RBA and recycled expanded polystyrene for better thermal properties.

2.3. The utilization of waste glass in concrete mixture

The EU countries produce approximately 30% of the total world's production of glass. However, the recycling rate of glass is around 60%. The utilization of clear glass without impurities is mostly into new glass. The clear waste glass is possible to recycled many times without significant degradation of quality and physical and chemical properties [46]. However, the large amount of unrecycled glass is still disposed in landfills [47]. The potential use of mixed glass with impurities is for concrete production. The utilization of waste glass as partial replacement of aggregate in concrete mixture is related with its chemical composition. The utilization of crushed or milled glass as partial replacement of sand or fines content in concrete mixtures is limited by potential of alkali-silica reaction (ASR) [48]–[50]. With regard to the risk of ASR, the maximum replacement rate of the aggregate is connected with the particle size of waste glass.

There have been published many studies which examine the possibility of the utilization of waste glass as aggregate in concrete. In these studies, the basic properties of aggregate and waste glass are usually compared. Further, the possibility of alkali-silica reaction (ASR) is verified. Furthermore, the influence on the mechanical properties of concrete with glass aggregate is examined. It was presented that the density of the glass is 2190 kg/m³ that is about 15% lower than the density of the sand. The water absorption of the waste glass is 0.39% which is 14% lower than the water absorption of sand [51].

2.3.1. The utilization of fine crushed glass in concrete mixture. The results of many studies showed that with the increasing particle size of the waste glass, the risk of ASR increases. It was verified that the maximum grain size that can be used is 0.9 to 1 mm and the maximal replacement rate is 20%. The replacement rate of recycled glass with the particle size up to 0.15 mm is 40% and for the size between 0.036 and 0.05 can be used up to 70%. The utilization of fine particles of waste glass as a replacement of sand positively influence properties of concrete. Some studies indicated that glass powder (the finest part of waste glass) is used to increase pozzolanic properties. Further, the reaction of glass powder and cement leads to the production of cementitious materials. These aspects positively affects the properties of concrete [52]. The very important for utilization of glass in concrete mixture is chemical composition of waste glass. Due to its high content of SiO_2 , the grinding waste glass is possible to use as partial replacement of silica fume or silica flour in HPC [53].

3. Possibilities of cement replacement in concrete production

Many more or less researched technologies how to reduce cement in concrete or how to reduce environmental impact of cement production or both were described. Among of emerging technologies are included high activation grinding, fluidized bed kiln, calcareous oil shale as an alternative raw material, use of steel slag as raw material for kiln, use of carbide slag etc [54]. Another method is the utilization of industrial by-products and waste materials, which have been used as supplementary cementing materials such as fly ash [55], silica fume [56], granulated blast-furnace slag [57], ceramic powder [58]–[60], recycled cement powder from waste concrete [61]–[63] and recycled gypsum (from recycled waste gypsum boards) instead of natural gypsum for cement production [64]. The main aim of the substitution is to reduce negative impact of cement production, due to its consumption of natural resources. The chemical composition of the concrete components and glass are cited in Table 1.

Table 1: The chemical composition of cement, glass, sand, silica fume, concret powder and brick powder [50], [60], [65].

Chemical composition	Cement [53]	Sand [53]	Silica fume [63]	Clear glass [53]	Crushed glass [53]	Glass powder [53]	Concrete powder [63]	Brick powder [68]
SiO_2 [%]	20.2	78.6	94.5	72.4	72.6	72.2	53.8	88.5
Al_2O_3 [%]	4.7	2.6	0.9	1.4	1.4	1.5	13.2	0.1
CaO [%]	61.9	7.1	0.4	11.5	11.7	11.4	13.6	1.0
Fe_2O_3 [%]	3.0	2.5	0.1	0.1	0.5	0.5	2.2	5.7
MgO [%]	2.6	0.5	1.6	0.3	0.6	0.8	2.6	0.8
Na_2O [%]	0.2	0.4	0.1	13.6	13.1	12.9	0.7	-
SO_3 [%]	3.9	-	-	0.2	0.1	0.1	-	-

The examples of materials which is possible to use as partial replacement of cementitious materials are shown on Figure 4 and 5.



Figure 4. The milled and grinding glass powder



Figure 5. The recycled cement powder from waste concrete

3.1. *The utilization of recycled cement powder from waste concrete as partial replacement of cement*

The use of recycled cement powder from waste concrete is one way to utilization of the finest fraction from recycled concrete. The major constituent of the fines content of recycled concrete is cement paste, which is possible to use as clinker raw material, because contains high concentration of CaO [11]. There were published some possibilities how to separate aggregate and attached mortar. One of them is the heat treatment and abrasion method. This method decreases aggregate content in recycled cement powder to 33%. Nevertheless, this procedure is not so efficient for reduction of CO₂ emissions because the saving is only up to 2%. If the new technique will be developed and aggregate content decreases to 2.4% the reduction rate of CO₂ emissions would be reduce to 10% [11]. Further, the complete separation of the cement paste and aggregate is a heat treatment between 300 and 500°C. The attached cement mortar is separated from aggregate during this process and then separated cement mortar is milled to cement powder and use as partial replacement of cement. It was verified that recycled cement powder is possible to use instead of 10% of cement in concrete mixture in this study [66]. The other way of attached cement mortar separation from aggregate surface is by microwave heating [67].

3.2. *The utilization of brick and ceramic powder as partial replacement of cement*

There were found that the use of fine aggregate from waste bricks and sanitary ware contribute to pozzolanic activity [68]. The replacement rate of cement in concrete or mortars by ceramic waste up to 20% had no effect to mechanical properties and modulus of elasticity [69], [70]. The other study showed that the maximal replacement rate of cement in concrete mixture is 15% when natural aggregate is used and 5% when 30% of natural aggregate is replaced by recycled aggregate from waste bricks [59].

3.3. *The utilization of grinding waste glass as supplementary cementing material in concrete*

The glass production is provided by melting silica, soda ash and calcium carbonate at high temperature [71]. Furthermore, the glass powder (fraction 0,038 – 0,045 mm) has high silica content (SiO₂ > 70%), high surface area and amorphous character [72]. These all factors suggested the potential of its utilization as an alternative supplementary cementing material in concrete [47].

4. Conclusion

The utilization of recycled materials for concrete and cement production is reviewed in this contribution. The results of cited references show many possibilities of utilization of waste materials from construction and demolition waste in cement and concrete production. On one hand, the use of these secondary materials as a full replacement of natural materials mostly leads to the mechanical properties decrease. On the other hand, when only the part of the natural materials is replaced, the quality of cement or concrete could be maintain. The clear benefit is the natural resources savings and often energy and CO₂ emissions savings that are depleted during cement and concrete production process.

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