Fine proportions of demolition waste recyclates in terms of functionality and application possibilities in building mixtures

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Abstract. A specific component of demolition waste from concrete and brick structures is the fines that remain after processing into granular recyclate and after sorting out the coarser fractions. In addition to brick and concrete recyclate, this can also include materials such as glass, ceramics (tiles, sanitary ware...), rubber and ornamental stone. These fine-grained wastes in this paper, a systematic review of fine-grained recyclates is elaborated with specification of their nature (inert-active) and a summary of their properties, or their modifications, to achieve the declared functionality. At the same time, an overview of the application possibilities (types of construction mixtures) in which the fines can contribute to the achievement of specific properties (e.g. self-compacting concretes, decorative plaster, mortars, railway concrete sleepers...).

1 Introduction

The use of construction and demolition waste not only reduces environmental burden by minimizing landfills but also preserves the finite raw materials. Recycled concrete and brick aggregates resulting from the demolition of old concrete and brick structures are available currently in large quantities. Coupled with shortage of non-reactive natural aggregates, there is an urgent need to use the waste aggregates. Many studies have proven that recycled coarse aggregates (RCA) can be an excellent substitution of natural aggregates for concrete production [1, 2]. In addition, the influence of concrete, brick and others ultrafine inert materials on the cement hydration was investigated. The results show that most of the minerals have an accelerating effect. They provide nucleation sites for hydration products and contribute in that way to a faster dissolution of cement grains. Minerals containing calcium were found to influence the early stage of hydration as well. These minerals shorten the dormant period of the cement hydration, the effect is known from limestone filler in self-compacting concrete [3]. Braga et al. [4] also show that the reduction of the cement content in mortar can be compensated by the presence of crushed concrete fines in the sand and studies show that brick powder is a promising material for the production of pozzolanic cement [5], mortar [6], and concrete [7], provided the material is of a particle size less than

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60 μm and the replacement ratio is up to 25% [8]. Glass waste and different types of ceramic waste were also a popular choice. Almost all research effort in question was focused on achieving concrete which would substitute ordinary concrete based on natural aggregates [9]. The pozzolanic activity of glass powder and properties of glass powder blended cement was evaluated. Also, the effect of using glass powder as cement replacement and as cement addition was studied in the term of physical and mechanical properties [10]. Considering the current development of the construction industry, we can see great potential in the recovery of glass waste. Buildings are increasingly glazed, which means that there will be a lot of waste glass at the end of the building's life cycle. A maximum reduction in Portland Cement clinker in cementitious binders, cement and concrete is one major step on the pathway to the decarbonization of concrete production by 2050 [11]. In contradiction to future technologies like CO2-capture and storage or clinker free, alternative cements, the development of binders and concrete with low clinker content is a practicable solution for decarbonization in building practice already today. This requires either the provision of new, low-clinker composite cements or the mixing of existing cements with a high portion of supplementary cementitious materials (SCMS) and microfillers to produce low-carbon concretes on an application-specific basis [12].

In 2015, a group mandated by UN Environment published the report "Eco-Efficient Cements" [9]. This report explains the central role cementitious materials play in our modern societies, as these materials constitute more than half of all manufactured materials. This report stresses that the majority of the growth in cement demand will happen in emerging countries. As an example, the demand will increase by 2 or 3 times in India during the next few decades (Figure 1). This increase in cement demand would have drastic consequences in term of CO2 emissions and resource depletion if the current industrial trend continues [11]. The report argues that action at the level of cementitious materials has the potential to deliver a major contribution to climate change mitigation. The report shows that there are low-cost solutions available and usable everywhere by low skilled workers and should be pushed forward by all governments and industry representatives. The UN report "Eco-efficient Cement" identifies two main routes that can fulfil the demand and deliver CO2 reductions in the relatively short term, which are as follows: increasing the substitution of clinker by supplementary cementitious materials and making more efficient the use of cement in downstream products (mortars, concrete) [11].

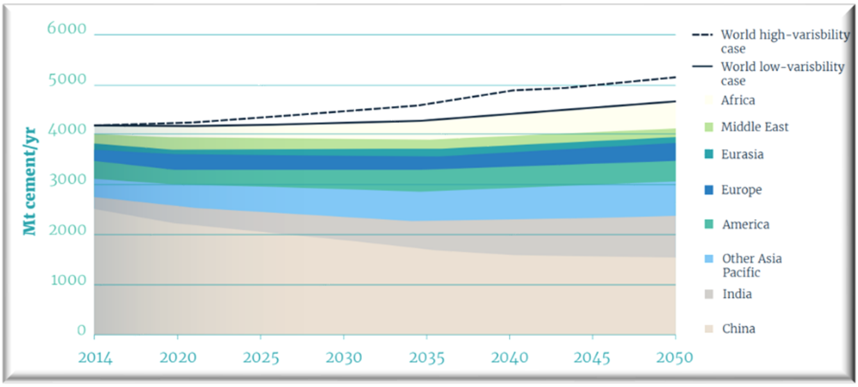

Fig. 1. Projection of cement demand from the IEA-CSI report [11].

To summarize, microfillers made from recycled materials would bring additional economic and environmental benefits to the building mixtures. In this paper, a systematic and comprehensive review of fine-grained recyclates is elaborated, focusing on recycled concrete, brick, glass, ceramic, rubber and ornamental stone. The aim is to focus and structure the knowledge of these materials in terms of the properties that influence their performance in a construction mixture. An overview of the application possibilities (types of construction mixtures) in which the fines can contribute to the achievement of specific properties (e.g. self-compacting concretes, fair-faced concretes, impermeable concretes ...) is elaborated. and a summary of their properties, or their modifications.

1.1 Fine- grained recycled materials and their characteristics

1.1.1 Recycled Concrete fines (RCF)

Traditionally, concrete rubble was either disposed in landfills or crushed and used as filling if there was a demand in the vicinity of demolition sites. However, when used as filling or backfilling, its potential is not fully exploited. The newly established environmental laws, or those soon coming into force, have led together with increasing environmental awareness and economic motivation to extensive research into concrete recycling for manufacturing new cement-based products. The primary effort is focused on a maximum possible replacement of primary materials, such as Portland cement and aggregates, in concrete production. Such an effort can contribute to sustainability of construction, because Portland cement is the most widely produced synthetic material [13] and its production contributes to approximately 5–7% of the global anthropogenic CO2 emissions [14]. It has become a common practice to replace a portion of aggregate in concrete with a recycled concrete aggregate [15-16], but little has been accomplished in the utilization of fine subsieve fractions, constituting about 15–50% of crushed concrete weight [17-18]. These fines are mostly the stripped paste/mortar and, besides small aggregate fractions, contain a portion of unhydrated clinker [18]. Some concrete examples and research results follow.

Recycled concrete fines in the Z. Prošek study [19], (RCF) were blended with fly ash, blast furnace slag and Porland cement to increase hydraulicity of the pastes. In addition to the control mixture, different combinations of components were used, resulting in 10 test formulations where the amount of RCF was constant and relatively high (50%). Because recycled concrete can reduce pH of the mixture, small portions of lime were also added to increase the alkalinity and promote proper formation of hydration product. The impact of individual additives on microstructure and mechanical properties of PC-based pastes containing recycled concrete was investigated. Relative compressive and tensile strength in bending after 90 days of curing were presented by authors [19], The values were calculated as the ratio of the compressive strength of pure cement paste (106.3 MPa) to the weight of PC in the pastes, as well as a ratio of tensile strength in bending of pure cement paste (6.0 MPa) to the weight of PC in the pastes. The results indicate that all the pastes containing RCF performed much better in bending. However, only the pastes containing fly ash outperformed control paste also in compression, which can be attributed to the formation of C-(A)-S-H gel in the vicinity of RCF grains in the presence of fly ash minerals.–The presented comprehensive study suggests that recycled concrete fines can be used in large amounts for production of concrete, and do not require thermal treatment for their activation by dehydration, especially when using suitable supplementary cementitious materials. The research [19] showed, that the 50 wt% substitution of Portland cement by mostly inert particles of finely ground recycled concrete led to a reduction of strength and stiffness. This deterioration of mechanical properties resulted from a less compact and more porous structure, even though the presence of recycled concrete promoted hydration of Portland cement by allowing better access of water to clinker grains. Recycled concrete acted as microfiller that reinforced the brittle cementitious matrix, thus increasing its tensile strength in bending after 90 days of hardening and reducing its shrinkage [19]. The study of *Junxia*

Li [20] investigated potential use of (RCF) as microsilica sand substitute in the production of engineered cementitious composite. The results clearly explained the influence of RCF size and content on ECC properties. Micromechanics-based design principle can be used for ingredients selection and component.

Huixia Wu [21] studied optimizing RCF/RBF replacement pattern (type) and replacement ratio can obtain sustainable mortar owning good micro–macro properties. Substituting RCF simultaneously for both 10% cement and 10% sand is recommended, and in this case, the RCF blended mortar has good mechanical strength and permeability resistance.

Veera Horsakulthai [22] studied an effect of recycled concrete fines on self-compacting mortars. The compressive strength, electrical resistivity, porosity, and water absorption of the RCF self-compacting mortars. The results indicated that the RCF was reactive, having a strength-activity index of 89.4% and 87.2% at 7 and 28 days, respectively. The porosity and water absorption coefficient increased, and electrical resistivity decreased with an increase in the RCF content. Based on the results of this study, the optimum RCF replacement ratio with minimal negative effect on the compressive strength is up to 20%.

1.1.2 Recycled Brick Fines (RBF)

Crushed clay brick powder used by various researchers come from two primary sources: discarded bricks from brick kilns which do not meet the required standards due to improper heating regimes producing over burnt or under burnt bricks, presence of cracks, warping, asymmetrical dimensions and other imperfections [23] or demolished masonry from construction sites (construction and demolition waste) [24]. Recycle concrete/brick fines with the maximum particle size below 0.15 mm have certain pozzolanic activity, and recycle brick fines (RBF) ground from clay brick waste have higher activity than waste concrete fines (RCF) ground from concrete waste [25]. Brick fines have irregular particle shape, resulting in relatively high-water demand in mixtures [26]. Reducing the particle size of RBF increases their reactivities and water demand [27]. Blending RBF at appropriate fineness and substitution rate can improve the resistance to autogenous shrinkage and drying shrinkage of concrete, but adding high volume of RBF declines the drying shrinkage resistance [28]. Introducing less proportion of WBF can improve the mechanical strength and permeability resistance, owing to its good pozzolanic activity and filling effects [29]; however, adding high-content (above 30%) RBF inevitably reduces the performance of blended cement-based materials [30]. Sand exploited from various sources often contains different proportions of or fines impurities (below 0.15 mm). Other scholars proposed to reuse waste concrete/brick fines as sand replacement to prepare eco-friendly cement-based materials, and the results highlighted that replacing sand by partial waste concrete/brick fines contributes to the strength development [31].

Some concrete examples and research results follow.

Huixia Wu study [21] showed, when incorporating RBF as partial sand replacement raises the compressive strength and substituting RBF for both 10% cement and 10% sand can prepare recycled mortar owning better compressive strength than the reference mortar M-Control. Optimizing RBF replacement pattern (type) and replacement ratio can obtain sustainable mortar owning good micro–macro properties. Substituting RBF simultaneously for both 10% cement and 10% sand is recommended, and in this case, the RBF blended mortar has good mechanical strength and permeability resistance.

Haoxin Li [2], studied the use of RBF in the production of cement-based red decorative plaster for walls. RBF can be used to adjust the cement-based decorative plaster color. This effect is related to the presence of Fe_3t in RBF. Plasters made with RBF have satisfactory water resistance and denser microstructure. The filler and pozzolanic effects contribute to the properties of the plaster, and the compressive and flexural strengths of plasters made with RBF are improved. However, excessive RBF leads to a decrease in the CH/SiO2 ratio in the paste and creates high requirements for water in the mixing of the paste. Thus, the compressive and flexural strengths of the plaster decrease as more RBF is used in the production. The addition of RBF helps to maintain the tensile bond strength, but excessive RBF has adverse effects on the tensile bond strength for RBF absorption. Nevertheless, plaster with 100% RBF has satisfactory tensile bond strength. The hydration and un-hydration phases of cement are found in the hardened paste. The CH content varies in different plasters, showing that the pozzolanic reaction proceeds to different extents. RBF increases the density of the plaster microstructure. The plaster with RBF exhibits better performance. As far as the economic and environmental benefits are concerned, it is feasible to use RBF in the production of red cement-based decorative plaster. These facts show that red cement-based decorative plaster can be produced with RBF. The economic and environmental analyses also show that the production costs of cement-based plaster will be reduced and that RBF environmental impacts will be minimized. Moreover, plaster made with RBF has better resistance to efflorescence for CH consumption. These results are important for the effective management and use of red brick waste in China and other developing countries.

1.1.3 Recycled Glass fines (RGF)

By Hongjian Du [32], the pozzolanic reactivity of recycled glass fines was experimentally studied at cement replacement levels of 0, 15, 30, 45 and 60% by weight. Results revealed that the concrete compressive strength was not decreased by the cement substitution after 28 days because of the pozzolanic reaction between RGF and cement hydration products, if the replacement is below 30%. Also, the resistance to chloride ion and water penetration continuously increases with increasing glass powder content up to 60% cement replacement. At 60% replacement level, the electrical resistivity and water penetration depth were reduced by 95% and 80%, respectively, while the compressive strength was maintained as 85%. These improvements in durability properties are due to the refined microstructures, particularly at the interfacial transition zone. Pore size distribution was measured to confirm the refinement in the capillary pores, which partially block the pathways for water and chloride ions, Hongjian Du also demonstrates that high performance concrete (improved strength and impermeability against chloride and water) could be achieved by using RGF as 15% additive, which contributes to the pozzolanic reaction instead of being inert fines for compact packing. Concretes incorporating RGF also have strength satisfactory in comparison with the controls and with the other additives. RGF can be incorporated from 20% to 30% as partial substitution of cement in concrete without affecting its compressive strength in medium or long terms. This work, based on the study of the effect of recycle glass fines on concrete properties, showed a good behavior of this mineral addition compared to the conventional SCM. As expected, the increase in w/b ratio lowers the compressive strength of concrete containing RGF at early age. However, the development of compressive strength seems to be more prominent with the increase of w/b ratio in the presence of glass powder in the long-term. This behavior reflects a slow and continuous pozzolanic activity of the glass powder in mixtures with enough free water available. In addition, the improvement of concrete durability in the presence of RGF is more important with increasing its rate of incorporation and/or w/b ratio. When comparing the effect of RGF with the other SCM, one can observe that RGF actions on concrete properties are like those of class F fly ash. Slag seems to develop significant effects at an early age in comparison with the other additions, but in the long term (from 91 days) their effects are equivalent. As recycle glass fines develops quite similar or even better effects than other SCM studied on concrete properties, it could be properly used as an alternative supplementary cementitious material where conventional SCM are not available [33].

1.1.4 Recycled ceramic fines (RCF)

The research program dedicated to the use of waste ceramics in form of tiles, roof tiles, bricks, and sanitary products to create concrete has been conducted by many scientists all over the world [34-35]. It was demonstrated [36] that the addition of recycled ceramic aggregate to conventional concrete improves its mechanical characteristics. Other study has shown that the addition of ceramic waste increases the resistance of concrete to aggressive chemical agents [37]. The recycled fine and coarse ceramic aggregate was successfully used to produce paving stones [38] and ordinary concrete [39-40]. Some researchers have conducted studies to assess the effect of recycled aggregate from ceramic sanitary waste [41]. The conducted research confirmed the possibility of using ceramic sanitary waste in the form of fine and coarse aggregate to produce concrete composites [42]. Furthermore, other studies have shown that although sanitary ceramics and ceramic kitchen utensils improve the mechanical parameters of concrete, waste brick ceramics not always positively affect its strength [43]. Taking all above facts into account authors decided to conducted research program aimed to determine the effect of the addition of a recycled ceramic fines RCF and recycled ceramic fine aggregate (RCFA) coming from damaged ceramic pots (white ceramics) on selected properties of concrete.

Some concrete examples and research results follow.

Paul O.Awoyera [44] focuses on the mechanical characterization of waste ceramic wall and floor tiles aggregate concrete. Ceramic wastes sourced from construction and demolition wastes were separated from other debris and crushed using a quarry metal hammer. Ceramic tiles were sieved into fine and coarse aggregates in line with standards. It can be concluded that, within the limited scope of the experiments carried out in this investigation, concrete made with RCA as a replacement for part of the natural aggregates can be considered a suitable alternative for normal concrete. In fact, where strength is concerned, it is even more suitable than conventional concrete.

J. Halbiniak [35] tested the mechanically processed crushed ceramic pots, which were added to the concrete mix in two ways: as a RCF and as a RCFA. The ceramic meal with a fraction below 0.25 mm was obtained by processing crushed pots using a mill and disintegrator. The pulverized ceramic material was added in 10%, 20%, and 30% of the cement mass. Recycled ceramic fine aggregate with a particle diameter up to 4 mm was created using only industrial mill. The aggregate obtained from pots was used to replace 20%, 30%, and 40% of the sand mass. It was found that, the concrete with 30% of RCF had higher compressive strength by 8.5% compared to the control concrete; concrete with RCFA slightly increased the mean compressive strength of concrete with its addition. The concrete in which 40% of sand was replaced by RCFA, achieved higher compressive strength of 2.8% compared to the control concrete. Results of the research program aimed to analyze the opportunities for using waste ceramic pots to produce watertight concrete. Ceramic pots damaged during the production process can be successfully used as a full-value additive in the production of cement composites; the addition of microfiller in the amount of 30% of cement mass yielded the concrete with the highest compressive strength, the lowest water absorption and the lowest penetration of water under pressure.

1.1.5 Crumb rubber fines (CRF)

I will also mention rubber in passing, even though it is not primarily waste of demolitions. Waste rubber in concrete applications is a perfect alternative because Styrene is the main component of rubber, which has a strong toxicity and is harmful to humans. That's mean, it will significantly reduce impacts on the environment when waste rubber can be recycled for this purpose. The new findings demonstrate that the high-strength concrete can be enhanced by optimal rubber particles in order to improve splitting tensile and flexural strengths, damping properties, and electrical resistivity. It is therefore recommended to consider the use of rubberised concrete (up to 10 wt. % crumb rubber) in designing railway sleepers as this will improve the service life of railway track systems and reduce wastes to the environment [45].

Sakdirat Kaewunruen [45] studied the potential of crumb rubber fines as a additive to concrete. Therefore, it has been deducted from the tests results of this study that the crumb rubber concrete can be considered as a reliable material for railway concrete sleepers, since its compressive strength meet the standard for sleepers manufacturing (55 MPa). Finally, by conducting vibration tests on rubberised concrete and using both the exponential curve fitting method (ECFM) and the logarithmic decrement method (LDM), it has been concluded that the crumb rubber has clearly improved the concrete's damping ratio, especially when using the 180&400 micro which resulted in an improvement of 100% comparing to normal concrete. It showed the best performance in all tests and meets the requirements of railway concrete sleepers. From the environmental perspective, the use of crumb rubber in concrete presents one of the best alternatives while dealing with rubber waste, as it will help both the environment protection and also the reduction in railway sleepers' cost. These results confirm the theory stating that the damping ratio of concrete improves with the increase in the size and the amount of rubber content as declared by Zheng at al. [46]. A damping ratio of 3% could easily reduce up to 20–30% of dynamic actions (bending, shear, and force); however, in order to suppress large-amplitude vibrations the damping coefficient should be around 4–5% [47]. Consequently, since the static and dynamic properties of the rubberised concrete (180&400 micron) meet the design standards, it should highly be recommended for concrete railway sleepers' manufacturing [48-49].

1.1.6 Recycled ornamental stone fines (ROSF)

Brazil is one of the largest producers and exporters of ornamental stones, producing more than 10 million tonnes in 2022 [50]. About 41% of the raw material becomes residue in plates cutting and polishing processes. Despite being classified as non-hazardous and inert, if incorrectly discarded, ornamental stone waste (OSW) can cause environmental problems such as silting of rivers, pollution of water sources and diseases to the population due to the fine particles [51-52]. In this sense, waste management regulations have been created, pressuring the generating sectors to provide solutions to promote correct disposal and recycling [53-54]. In this case, it is mainly waste generated during the extraction of this material. But in the end, this material in the same composition is only processed for incorporation in buildings as tiles, kitchen countertops, decoratives, pavements and others. These wastes in civil construction is a viable alternative since this sector consumes large volumes of natural resources and is prone to absorb solid waste. In this sense, OSW can be used as a filler in concrete due to its particle size distribution (PSD) comprising high contents of fines and superfines [55].

Ariel Miranda de Souza [55] studied the high incorporation of ornamental stone waste as a filler to replace cement consumption (f/c) and the variation of powder volume (Vp/Vt) in self-compacting micro-concrete. The results showed that: Mixtures with f/c ratios between

1.71 and 2 and with Vp/Vt between 0.35 and 0.4, with cement consumption varying between 263.35 kg/ m3 and 320.36 kg/m3, as they are the most eco-efficient for a conventional strength (class 20), can be used as grout and as simple reinforced concrete, indicated for the manufacture of non-structural precast elements, and structural elements such as foundations, beams, and slabs in weak environmental aggressiveness, such as rural and submerged environments. Mixtures with a f/c ratio between 1 and 1.19, with cement consumption varying between 360.62 kg/m3 and 470.7 kg/m3, as they have a strength in the 30 MPa class, and still have superior eco-efficiency compared to conventional mixtures, can be used as grout and structural reinforced concrete in highly aggressive environments, such as maritime and industrial regions, and even in prestressed elements in environments with low risk of deterioration. For a low-cost self-compacting concrete, low cement consumption, and high residues incorporation, the strength can compensate its manufacture, producing a more fluid concrete without the need for compaction equipment, reducing the concreting workforce, decreasing the hydration heat of cementitious materials, and allowing a variety of applications such as structural elements, slender and thin pieces, grout, among others, with the prerogative of being a more sustainable concrete.

Peerzada Danish [52] focused on the use of pozzolanic material like Metakaolin (MK) as a mineral admixture and non-pozzolanic material like Recycled marble fines (RMF) as a filler material. Both types of materials have a positive effect on the fresh, hardened and durability state of selfe-compacting concrete (SCC). The use of MK plays an important role in decreasing the environmental pollution by way of lesser carbon dioxide emissions. The use of WMP reduces the segregation, bleeding and cost of production of SCC.

2 Conclusion

To summarize, microfillers made from recycled materials would bring additional economic and environmental benefits to the building mixtures. Studied an effect of recycled concrete fines on self-compacting mortars. Based on the results of this study, the optimum RCF replacement ratio with minimal negative effect on the compressive strength is up to 20%. As far as the economic and environmental benefits are concerned, it is feasible to use recycled brick fines (RBF) in the production of red cement-based decorative plaster. Recycled glass fines (RGF) can be incorporated from 20% to 30% as partial substitution of cement in concrete without affecting its compressive strength in medium or long terms. As recycle glass fines develops quite similar or even better effects than other SCM studied on concrete properties, it could be properly used as an alternative supplementary cementitious material where conventional SCM are not available. The research program dedicated to the use of waste ceramics in form of tiles, roof tiles, bricks, and sanitary products to create concrete has been conducted by many scientists all over the world. It was demonstrated that the addition of recycled ceramic aggregate to conventional concrete improves its mechanical characteristics. I will also mention rubber in passing, even though it is not primarily waste of demolitions. Waste rubber in concrete applications is a perfect alternative because Styrene is the main component of rubber, which has a strong toxicity and is harmful to humans. The last material, I want to mention, is ornamental stone. In this case, it is mainly waste generated during the extraction of this material. But in the end, this material in the same composition is only processed for incorporation in buildings as tiles, kitchen countertops, decoratives, pavements and others. These wastes in civil construction is a viable alternative since this sector consumes large volumes of natural resources and is prone to absorb solid waste.

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