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Pre-demolition concrete waste stream identification: classification framework

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ABSTRACT

Demand for high quality recycled concrete aggregates (RCA) to offset the use of primary materials is significantly rising due to circular economy goals and high-value reuse of concrete. The quality of RCA significantly affects their availability for new concrete production due to the variability of parent concrete streams. The optimization of recycling procedures is under development to improve the quality of RCA, however, the costs and energy efficiency of such processes are of practical concern. With this in mind, this paper presents a new framework for reducing the variability of RCA quality by identifying concrete members before their demolition. The goal of identifying demolished concrete members from a structure is to provide groups of concrete members with similar mechanical and chemical properties through a systematic classification of the structural members.

The quality assessment of concrete structures and their mechanical and chemical (composition, contamination) properties prior to demolition is generally recognized as challenging due to the absence of guidelines and the lack of easy-to-use in situ characterization techniques. This paper proposes experimental approaches that can non-destructively determine the properties of concrete structures, with a major emphasis on the measurement of the chemical composition of concrete before demolition. Characteristic quality indicators to classify concrete members are first proposed and can be instrumental in setting up future studies. A new method is proposed for in situ chemical composition testing of existing concrete structures; assuming that no records about the parent concrete are available. Next, the challenging parameters for in situ, non-destructive measurements are outlined. The practical application of the proposed method and its uptake in industry can potentially unlock a huge potential for optimized material recovery and contribute greatly to a fully circular construction industry.

1 Introduction

Globally, the construction industry is expanding rapidly [1], while transportation infrastructure is facing significant challenges due to aging, rapid growth in traffic loads, and changing circumstances of existing structures (natural and man-made resilience threats) [2]. As a consequence, a significant amount of construction and demolition waste (CDW) is generated. CDW contains concrete, brick, wood, metal, drywall, plastics, glass, and others [3], of which concrete waste forms the largest part. In Europe, CDW is assessed to be 25–30% of the total waste [4], whereas the level of recycling is still highly variable between the member states [5]. Most countries globally and within the EU still have low performance in CDW generation, management, and recycling [5] because of ineffective CDW regulations; poor data quality; poor reverse logistics; and a low market readiness for secondary materials [3]. Other sources of demolished concrete are residential and non-residential buildings, civil engineering structures, and the building and pavement industries [6], amongst others. Demolition of concrete structures can have various causes. Primary causes of structural failures, and consequently demolition are poor construction procedures, inadequate assemblage of concrete members, and inadequate behaviour under load [7, 8]. In the Netherlands, for example, the majority of bridges and viaducts in the main highway network have been demolished in the past for functional reasons (improved traffic flow on the road network and railway construction), and the rest were demolished due to technical reasons such as insufficient load-bearing capacity (design loads, accidental overload, deterioration) [9]. Fig. 1. gives an example of demolition. The Hoog Burel viaduct over the A1

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in the Netherlands was more than 50 years old, and the concrete had deteriorated.

Such demolitions have so far primarily been carried out without significant preselection, in particular, without any preselection of concrete. Furthermore, the recycling process principally consisted of simply crushing the waste concrete, which inevitably entailed a degradation in quality [11]. Although in the past two decades, significant effort has been made towards the advancement of concrete recycling and many achievements have been made in both the treatment and application of recycled concrete aggregates (RCA), their use is still very limited in new concrete structures. This is due to the fact that the recycling is mainly focused on mixed concrete streams and, therefore, the quality of RCA is a major concern for concrete producers (Fig. 2).

To address this issue, simple, non-destructive in situ characterization techniques that enable pre-selection prior to demolition and waste stream separation based on concrete properties are required. With this in mind, the primary goal of this paper is to propose a workflow for use in demolition projects that is based on in-situ quality assessment of parent concrete and non-destructive testing. The paper proceeds as follows: Section 2 presents the current demolition and recycling practices that do not rely on selective demolition; Section 3 examines concrete input properties for selective demolition; Section 4 presents a specific workflow towards a selective demolition-based recycling of concrete; Section 5 presents non-destructive in situ concrete characterization techniques; Section 6 outlines further research needed on testing of concrete composition; and Section 7 concludes the paper.

Fig. 1. Demolition of Hoog Burel viaduct (A1), the Netherlands: a) before demolition, b) during demolition (November 2022). Credits go to Rijkswaterstaat [10]

Fig. 2. Mixed concrete streams at the recycling plant

2 Demolition and recycling without prior concrete characterization

The way we handle waste now is based on several EU guidelines, such as the Circular Economy Action Plan [12], the EU Directive 98/2008/EC [13], the EU Directive 2018/851/EC [14], the EU Construction and Demolition Waste Management Protocol [15], and the Guidelines for Waste Audits Before Building Demolition and Renovation [16]. However, concrete producers, construction engineers and real state owners are sceptical towards recycled aggregate concrete since RCA are typically heterogeneous [17] and of lower quality than natural aggregates [18]. In particular, engineers are faced with uncertainties when they have the opportunity to design structural recycled aggregate concrete members [19]. Quality assurance and certification are of paramount importance in order to address these reservations. It is very difficult, if not impossible, to demolish a concrete structure for which there is prior knowledge about the origin and properties of all concrete components. Information about the composition (cement, aggregates, fibres, coating) of each concrete member (strength class, with/without reinforcement, type of reinforcement), and their degree of contamination, is difficult to obtain. Furthermore, they may have been exposed to different environmental conditions (under varying conditions of drying and wetting, chloride environment, carbonation, chemical attack, alkali-aggregate reactions, etc.) [20].

Demolished concrete members can be crushed and processed on site with mobile crushers, or they can be transported to the recycling plant [21]. Preliminary manual sorting is conducted in order to eliminate hazardous materials (e.g., bituminous roofs) and further sorting with magnet pads to segregate metals [22]. Within such a process, there have also been recent advances in automating and robotizing the procedure. For example, ZenRobotics is an advanced and recently applied technology for efficient sorting of input materials (metals, wood, stone, and inert materials) with a heavy-duty picker sorting line (Fig. 3). ZenRobotics uses standard industrial robots and, depending on the application, equips them with a variety of sensors, detectors, and scanners, along with artificial intelligence software, to ensure maximum efficiency. The unit contains near-infrared spectroscopy, hyperspectral imaging sensors, a 3D sensor system, a high-resolution RGB camera, a metal imaging sensor, and a visual light spectrum sensor [23].

As for the recycling process, RCA are produced using the same equipment traditionally used in quarries for the production of natural aggregates, and their appearances are shown in Fig. 4. The most commonly used crushers are jaw and impact crushers[24].

The traditional production processes result in RCA with suitable properties for concrete, provided the CDW are of good enough quality after the initial separation. However, better recovery rates, faster and more efficient production, higher quality recycled aggregates, and additional types of recovered materials (e.g., recycled fines and cement) with suitable quality may be obtained with technologically advanced processes.

Examples of such advances are the Smart Crusher and Concrete to Cement and Aggregate (C2CA). The Smart Crusher separates concrete waste into gravel, sand, and cement with minimal damage to each of these constituents. This is achieved by adjusting the crushing force to an intermediate value between the average compressive strength of the aggregates and that of the hardened cement paste [25, 26]. In order to exert the right force on the aggregates, crushing and grinding are combined. C2CA technology combines a mechanical-based process, the Advanced Dry Recovery (ADR), with a thermal-based one, the Heating-Air Classification System (HAS). Both are mobile technologies suitable for on-site recycling of end-of-life concrete waste. The combination of these technologies is used to recover concrete waste into three product streams: coarse recycled aggregates (4–12 mm), fine recycled aggregates (0.25–4 mm), and an ultrafine fraction (<0.25 mm). While ADR is a mechanical system that crushes and sorts wet concrete wastes according to their particle size, HAS uses a combination of thermal and air classification methods to separate and activate the hydrated cement paste [27].

At the moment, all of these technologies are more expensive and more energy-consuming relative to established ones, making such recycled aggregates economically unviable as a competitive alternative to concrete made of natural aggregates. The energy consumption of RCA production was measured and plotted against the water absorption of coarse RCA in conventional and advanced recycling processes [28]. On the one hand, energy consumption was up to 62 times higher with advanced recycling processes than in the case of ordinary concrete recycling. On the other hand, water absorption has decreased.

Fig. 3. ZenRobotics technology heavy picker sorting line [23]

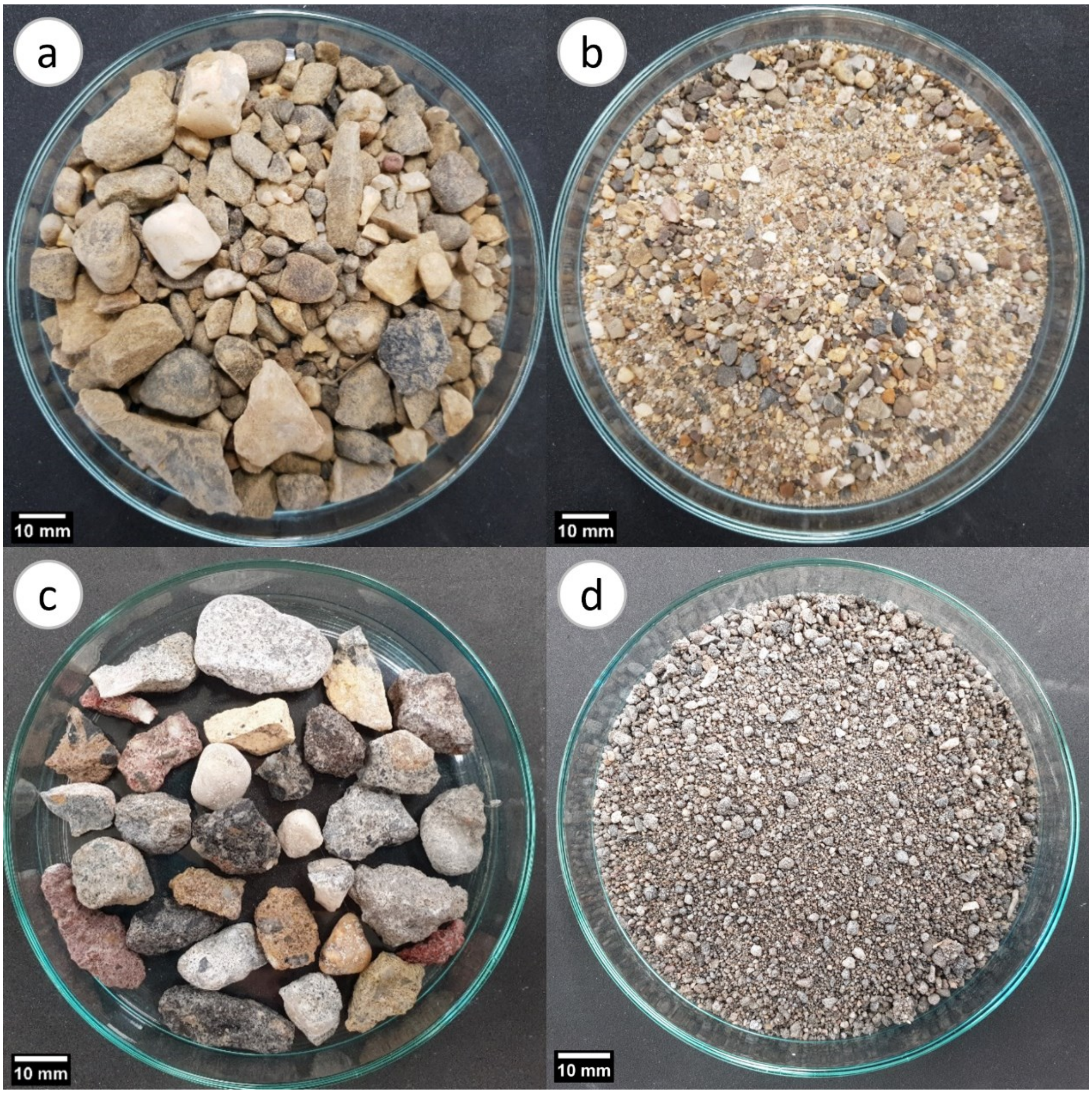

Fig. 4. Crushed natural materials (a) gravel and (b) sand versus recycled concrete aggregates (c) coarse and (d) fine

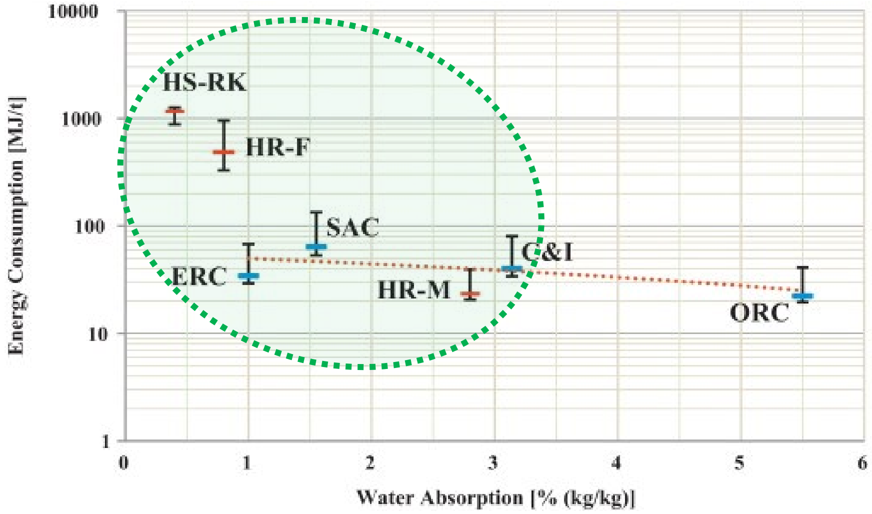

Fig. 5. Energy consumption per metric tonne (allocated to fine and coarse fraction) vs water absorption of RCAs subjected to advanced recycling processes. ORC (ordinary recycling); ERC (eccentric rotor crusher); C&I (compression and impact); SAC (screw abrading crusher); HR-M (heating by microwave oven and rubbing); HR-F (heating by kerosene furnace and rubbing); HS-RK (heating by rotary kiln and sorting), adopted from [28]

In addition, none of these advanced recycling techniques can recognize the quality of the input concrete waste. Such information can be of extremely high value for the wider application of RCA in producing structural concrete, that is, recycled aggregate concrete [29]. Therefore, selective/gradual demolition and sorting of concrete waste is another route for ensuring the correct management of recycled material. However, this route is not a preferred practice by demolition contractors for a number of reasons, such as insufficient space at the demolition site, too little time for additional sorting, or excessively low efficiency due to small quantities of waste to be sorted in different streams [30]. Furthermore, there are no specific workflows or visualisation tools established for selective demolition. Moreover, selective demolition was shown to induce high costs for the demolition sector [31]; the actual effort, if measured in time, skills, and labour, is significantly higher than for conventional demolition [5]. However, adaptive planning of the deconstruction works and ways of optimising cost-effective processes can also lead to considerable reductions in deconstruction duration and costs [31, 32]. In addition, if design codes emphasise the environmental aspects of the construction and give designers more opportunities for material sourcing, the chances of reuse through smart demolition and/or selective dismantling can be enhanced [32].

3 Concrete input properties for selective demolition

Visualisation tools allow for selective dismantling planning and therefore also allow one to foster demolition practices according to waste management priorities [33]. For correct concrete for waste management, it is necessary to define characteristic quality indicators for parent concrete. The RCA properties and parameters affecting new concrete are water absorption, composition, alkali-silica reactivity, contamination, and other critical parameters that may be related to compressive strength. Those parameters and their effect on new concrete are further examined, which led to the selection of key characteristic quality indicators for parent concrete screening in Section 3.5.

3.1 Compressive strength of parent concrete

The characteristic concrete compressive strength at 28 days is the value used by structural engineers for the design of new concrete structures. By evaluating fundamental parameters such as the compressive strength of parent concrete before demolition, crucial properties of RCA before their use in new concrete can be predicted. One of the distinguishing features of RCA is their water absorption. In a systematic literature review, Silva et al. [34] concluded that the increasing strength of the parent concrete may cause a reduction in the water absorption of the resulting RCA.In fact, Kou and Poon [35] examined the effect of the wide range of parent concrete strengths on the water absorption of RCA. RCA, derived from stronger parent concrete, had lower water absorption values. This effect was more distinct for RCA, with a maximum particle diameter of 10 mm compared to 20 mm [35].

Table 1 summarizes experimental data from the literature on the 28-day compressive strength of fine or coarse RCA concrete in relation to the parent concrete´s source and strength. It must be noted that in the majority of reviewed studies in the literature, the properties of the parent concrete were unknown, and RCA was produced from a mix of concrete waste from different sources and of unknown quality [36-40]. Therefore, such studies were not reported in Table 1. Nonetheless, these studies demonstrated how difficult it is to explain the properties of new concrete with RCA when information on the parent concrete's quality is unavailable.

The compressive strength of concretes with coarse as well as fine RCA fluctuated: it was higher, the same, or lower compared to a reference concrete. The compressive strength is rather sensitive to the high replacement level of RCA (100%), irrespective of the binder composition or cement content, as earlier reported [20]. As Table 1 shows, there is no significant difference between the sources of parent concrete: field or lab concrete, however, there is a significant difference with regard to their compressive strengths. Pedro et al. [41] studied the effect of using RCA (100% replacement of natural coarse aggregates) from different sources (precast rejects or laboratory concrete, with target strengths of 20 MPa, 45 MPa and 65 MPa) on properties of new concrete mixes with target strengths of 20 MPa, 45 MPa and 65 MPa, respectively. The loss of compressive strength of concrete with RCA was less for mixes with higher target compressive strengths (45 MPa and 65 MPa) compared to mixes with lower target compressive strengths (20 MPa). This finding is in line with other studies [42, 43]. The results showed that in terms of compressive strength, the replacement of 100% natural coarse aggregates would be possible when RCA are produced from parent concrete with a minimum compressive strength of 60 MPa [43]. In another study [44], more representative for field-demolished concrete, the compressive strength of parent concrete was 35 MPa and 23 MPa (a 40-year-old highway bridge). The new concrete mixtures were designed with a target 28-day compressive strength of 35 MPa. Concrete with 100% coarse RCA had an 8% lower 28-day compressive strength when produced with the same effective water-to-cement ratio as normal aggregate concrete, while other properties (shrinkage and creep) were comparable [44]. The study by Lotfi et al. [27] demonstrated that recycled aggregate concrete achieved higher compressive strength compared to natural aggregate concrete up to 30% at early ages, and after 90 days this difference became lower, at 5%. In terms of concrete deformations and durability, the concrete mixtures made with RCA derived from parent concrete with higher strength had lower drying shrinkage and higher resistance to chloride ion penetration [35]. It has also been reported that the compressive strength of parent concrete increases its resistance to fragmentation [45]. Overall, studies highlight the need to determine the strength of parent concrete, based on which realistic qualities can be targeted for recycled aggregate concrete [46].

Table 1. Parent concrete strength and 28-day compressive strength of concrete with RCA produced from respective parent concrete

	Parent concrete		28-day compressive strength of concrete with RCA produced from parent concrete													
	*Source/recycling technique	Strength														
Fine RCA			**0%**	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**40%**	**45%**	**50%**	**60%**	**75%**	**80%**	**100%**
Evangelista [47]	Lab, jaw crusher	29.6 MPa	59.3		59		57.3		57.1			58.8				54.8
Levy [48]	Field (6 months old concrete)	25 MPa	48.5				56.1					46.3				46.6
Yaprak[49]	Lab, jaw crusher	C30/37	45		42		41		40	38		36				29
Pereira [50]	Lab, jaw crusher	37.3 MPa	39.5		40				38.6			37.6				38.6
Pereira (SP1)[50]	Lab, jaw crusher	37.3 MPa	53.3		53.7				51			47.8				45.1
Pereira (SP2)[50]	Lab, jaw crusher	37.3 MPa	65.2		64.6				65.4			63.2				63
Khoshkenari (AW)[51]	Lab, jaw crusher	30 MPa	38													27.9
Khoshkenari (SP)[51]	Lab, jaw crusher	30 MPa	38													32.8
Cartuxo [52, 53]	Lab, jaw crusher	C30/37	49.37		51.17				47.21			43.53				41.2
Cartuxo (SP1)[52, 53]	Lab, jaw crusher	C30/37	66.79		63.86				61.65			58.73				47.36
Cartuxo (SP2)[52, 53]	Lab, jaw crusher	C30/37	80.64		77.41				71.73			69.31				64.72
Bogas (NC)[54]	Lab, jaw crusher	C25/30	50.2				49.9					47.4				43.1
Bogas (HC+SP)[54]	Lab, jaw crusher	C25/30	81				72.7					67.4				58.8
Bogas (HC+SP+AEA)[54]	Lab, jaw crusher	C25/30	67.9				61.8					52.1				44.9
Evangelista[55, 56]	Lab , jaw crusher	28.7 MPa	33.6		32.1				32.7			32.8				30.7
Coarse RCA			**0%**	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**40%**	**45%**	**50%**	**60%**	**75%**	**80%**	**100%**
Kou [35]	Lab, jaw crusher	35.8 MPa	70													50
Kou [35]	Lab, jaw crusher	51.1 MPa	70													55
Kou [35]	Lab, jaw crusher	61.8 MPa	70													62
Kou [35]	Lab, jaw crusher	87.9 MPa	70													70
Kou [35]	Lab, jaw crusher	101.7 MPa	70													72
Pedro [41]	Rejected concrete produced by precast concrete company	20 MPa	24													22
Pedro [41]	Rejected concrete produced by precast concrete company	45 MPa	39													35
Pedro [41]	Rejected concrete produced by precast concrete company	65 MPa	71													68
Radonjanin [57]	Field and lab	C30/37 and C45/55														44.2
Thomas [58]	Field	25 MPa	35.8					34.6				33.1				30.2
Andreu [43]	Rejected concrete produced by precast concrete company	100 MPa	102.1				108					104.8				108.5
Andreu [43]	Lab, jaw crusher	60 MPa	102.1				102.5					103.1				100.8
Andreu [43]	Rejected concrete produced by precast concrete company	40 MPa	102.1				104.3					96.8				91.2
Tošić [44]	Field (40 years old concrete)	35 MPa and 23 MPa	40.7													37.4
Geng [59]	Lab, jaw crusher	37.5 MPa	39.2													38.9
Geng [59]	Field (40 years old concrete)	38 MPa	39.2						30.8			30.1				25.9

The strength of the parent concrete may also have an impact on the amount of energy required for crushing. In the context of crushability tests, there are no data on the impact of the physical and mechanical properties of concrete on the energy consumption of a crusher during concrete crushing. For this reason, hard rocks will be discussed because of their similarities with concrete (artificial rock). Laboratory studies showed that the crushability of hard rocks is directly associated with the rock strength and mineralogical composition [60]. Rocks with a higher uniaxial compressive strength are "harder" to crush resulting in an increased share of larger particles and the need to use more energy for crushing [61]. Fig. 6 shows the dependence of the specific crushing energy on the compressive strength of the rocks [61]. In the same study, it was shown that fracture toughness and tensile strength also significantly affect the crushing energy. The impact of bulk density is not large, while hardness has only a minor impact. It is believed that, similar to the increase in energy with the strength of rock, concrete with a higher strength class consumes more energy for crushing in order to achieve the required particle size. During the size reduction processes in a jaw crusher and rod mill for quartz ore (density 2800 kg/m^3) with a density slightly higher than that of normal concrete (2400 kg/m^3), crushing and grinding energy consumption increase when finer size fractions of the product are desired [62], Fig. 7.

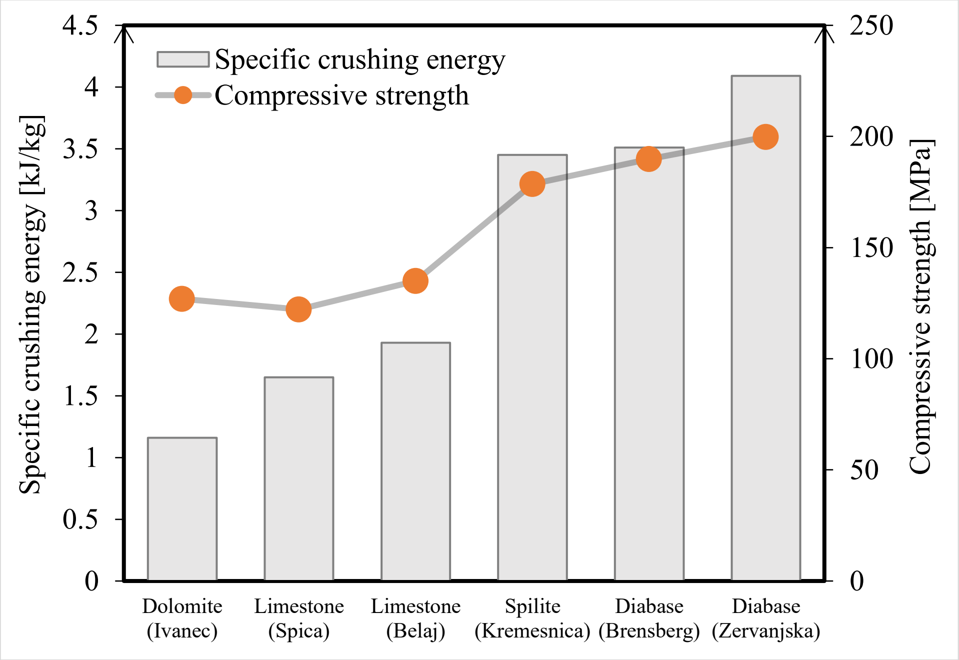

Fig. 6. Dependence of crushing energy on the compressive strength for various rocks [61]

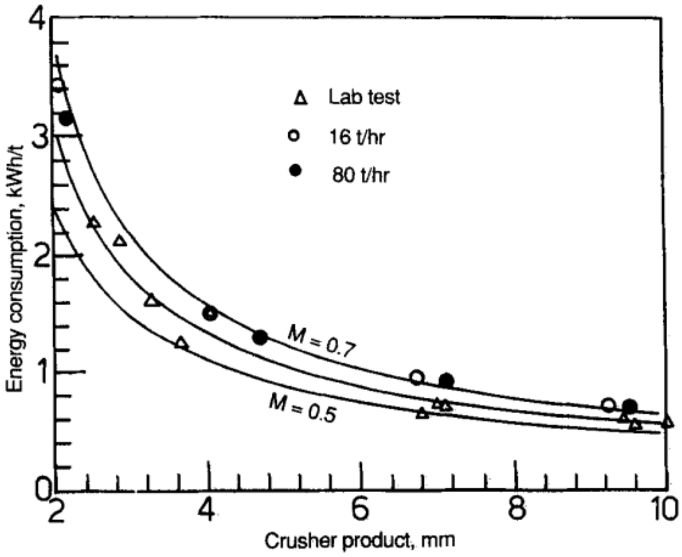

Fig. 7. Energy consumption in different crushing flowsheets, adopted from [62]

3.2 Composition of parent concrete

RCA are the least homogeneous in mechanical, chemical, and composition properties, since they originate from many different concrete waste streams. The chemical composition of the CDW, and therefore of the RCA, shows great variability [63]. The element with the highest average content is Si (47%), with values ranging from 8 to 77%. The proportion of CaO is also high (20% on average) and varies between 4 and 47%. Other components such as Al, Fe, Mg, S, and different alkalis follow as secondary elements. Other minor elements (Mn, P, Sr, Ti), may be present as well. Testing the parent concrete composition can provide two types of information, composition of major components in concrete and possible minor elements and contamination. Other reasons for testing the composition of concrete components before demolition are discussed below.

3.2.1 Identification of cement type

This information can assist in deciding on the application for recycled material. For example, based on cement type, one can decide whether the fine recycled concrete aggregates (fRCA) would be valuable for:

- Alternative raw materials

− mineral addition for clinker manufacturing. If the use of RCA in concrete mix design is limited by their physical or chemical properties (high absorption, sulphates or alkalis content, etc.), they can be used as raw materials for cement production [63]. The studies show that if the RCA composition, cement type, and cement quarry composition are known, it is possible to produce Portland clinker using RCA as raw materials [63-66]. Schoon et al. [64] incorporated the concrete fines in cement raw meal replacing siliceous materials due to the high SiO_2 contents of recycled materials. However, the percentages of RCA incorporation in the cement raw meal vary greatly, mainly due to the variation in RCA's chemical composition and the use of different natural raw materials (clays and limestone). It was shown that the maximum incorporation rate is mainly between 10–20% (50% of the 180 raw meal calculations), occasionally lower than 5% (13%), or higher than 30% (17%) [63]. The incorporation rates of CDW in an OPC clinker are directly controlled by the CaO or SiO_2 content [63]. The use of CDW for cement production requires better taking into account the effect of the natural raw materials and the RCA chemical composition variability. This is an example of how knowing the composition of RCA can improve clinker manufacturing by avoiding the addition of undesired components, such as clays. Other study reported a greater amount of phyllosilicates in the fine fraction compared to the other fractions [67]. Therefore, the authors indicate that if one is to use recycled fine fractions in mortars and concrete, careful sorting must be carried out to limit the presence of clays.

− pozzolanic materials [68], in which case the fine fraction of RCA should contain adhered mortar that consists of pozzolanic materials such as fly ash, silica fume, and naturally calcined pozzolana and has a siliceous or silico-aluminous composition as defined by EN 197-1:2011. It should be noted that fRCA and other pozzolanic materials have to be heated. It indeed has an environmental and economic impact, but it may result in more valuable material.

− fillers [69-72], the candidates would be fRCA with a high CaO or SiO_2 content. These candidates would be potential alternatives to traditional fillers such as limestone and quartzite.

- As an activator for ground granulated blast furnace slag and pozzolanic materials

Recycled concrete fines can be used for blended cements with the role of an activator. For example, thermally treated fRCA, when dissolved in water, can activate ground granulated blast furnace slag [73] or fly ash [74]. When combined with slag cement, the fine fraction of RCA improves compressive strength when compared to reference mortar (70% slag + 30% CEM I 42.5N) by providing lime for slag dissolution [75]. This occurs only if fRCA originates from OPC-based concrete, which can be known only if parent concrete composition is known.

- CO_2 sequestration

If CO_2 sequestration is the goal of using RCA, the most suitable cement type in adhered mortar in RCA is OPC, which contains the highest levels of CaO and calcium hydroxide ($Ca(OH)_2$) that can react with CO_2. The addition of fly ash or ground granulated blast furnace slag in partial substitution of OPC decreases the initial content of CaO in the cement matrix, and consequently, it lowers the amount of $Ca(OH)_2$ to be formed as a result of the cement hydration reaction.

- Durability aspect

When the concrete contains cement with high Al_2O_3 content, such as fly ash- (CEM II) or slag-based cement (CEM III), chloride binding by the cement matrix significantly increases (decreasing free Cl^- in the pore solution), as compared to reference concrete made without fly ash [76], which is beneficial for the application of such recycled material in new concrete, where chloride ingress resistance is required. This is yet another example of how knowing the composition of cement in parent concrete can have a beneficial impact on the durability of new concrete with RCA.

3.2.2 Identification of aggregate type

The aggregates of the concrete to be recycled have a large influence on the quality of the future recycled aggregates. For example, as shown in Table 1, different aggregate types lead to different compressive strengths. Furthermore, knowing the composition of aggregates in the parent concrete would assist in determining whether such aggregates would be suitable for the production of fillers usually used for production of concrete, such as limestone filler. In the study of Oksri-Nelfia et al. [72], parent concrete was made with limestone aggregates. Recycled crushed concrete fines (RCCF) had particles with a diameter smaller than 80 µm. The results show that the influence of RCCF on cement hydration is similar to that commonly observed for limestone filler. Fines of up to 25% can be used without affecting the properties of mortars [72]. In another study, Schoon et al. [64] used recycled concrete fines in cement raw meal to replace siliceous materials because the recycled concrete fines had a high SiO_2 content. Knowing the composition of aggregates in the parent concrete may prevent damage to the new concrete with RCA at high temperatures. It has been found that the performance of the recycled aggregate concretes was inferior to that of natural aggregate concrete under high-temperature in terms of the residual properties [77]. The rate of crack growth increased as the temperature rose. This behaviour was explained by the presence of flint in the original aggregates of RCA, which increased in volume during heating [78, 79]. Together, these studies [64, 72, 77] indicate that aggregate characterization in parent concrete is greatly important for predicting the properties of RCA.

3.3 Appearance of sound and potentially damaged concrete

A general definition of the appearance of potentially unhealthy or healthy concrete does not exist [80]. The appearance of a concrete surface can change as a result of ageing, loading, or interaction with the environment to which it is exposed [81], as illustrated in Fig. 8. Newly built reinforced concrete is approximately homogeneously coloured, whereas a long-used concrete structure can suffer for multiple reasons (Figs. 8a–b). Concrete can be painted or coated (Figs. 8c–d). Efflorescence usually appears as a white coating on the external surface of a concrete slab. A typical example of efflorescence formed by deposits of $CaCO_3$ is shown in Fig. 8e. The appearance of algae is demonstrated in Fig. 8f. The signs of unhealthy concrete are mostly visible from the surface as disintegrated concrete or severe cracking, Fig. 8g-h. If one wants to study any deleterious effects in depth from the surface, then the samples need to be extracted and analysed in the laboratory. The major deleterious effects, chloride ingress, sulphate attack, and alkali aggregate reactions and their assessment will be further discussed in detail in Section 3.4. These three mechanisms are selected as being critical for concrete contamination and, therefore, need to be considered in the selective demolition of concrete. Other deleterious effects are not addressed, such as carbonation, freeze-thaw attack, and fire. In fact, they do not introduce deleterious contaminants in the concrete that will affect the quality of RCA.

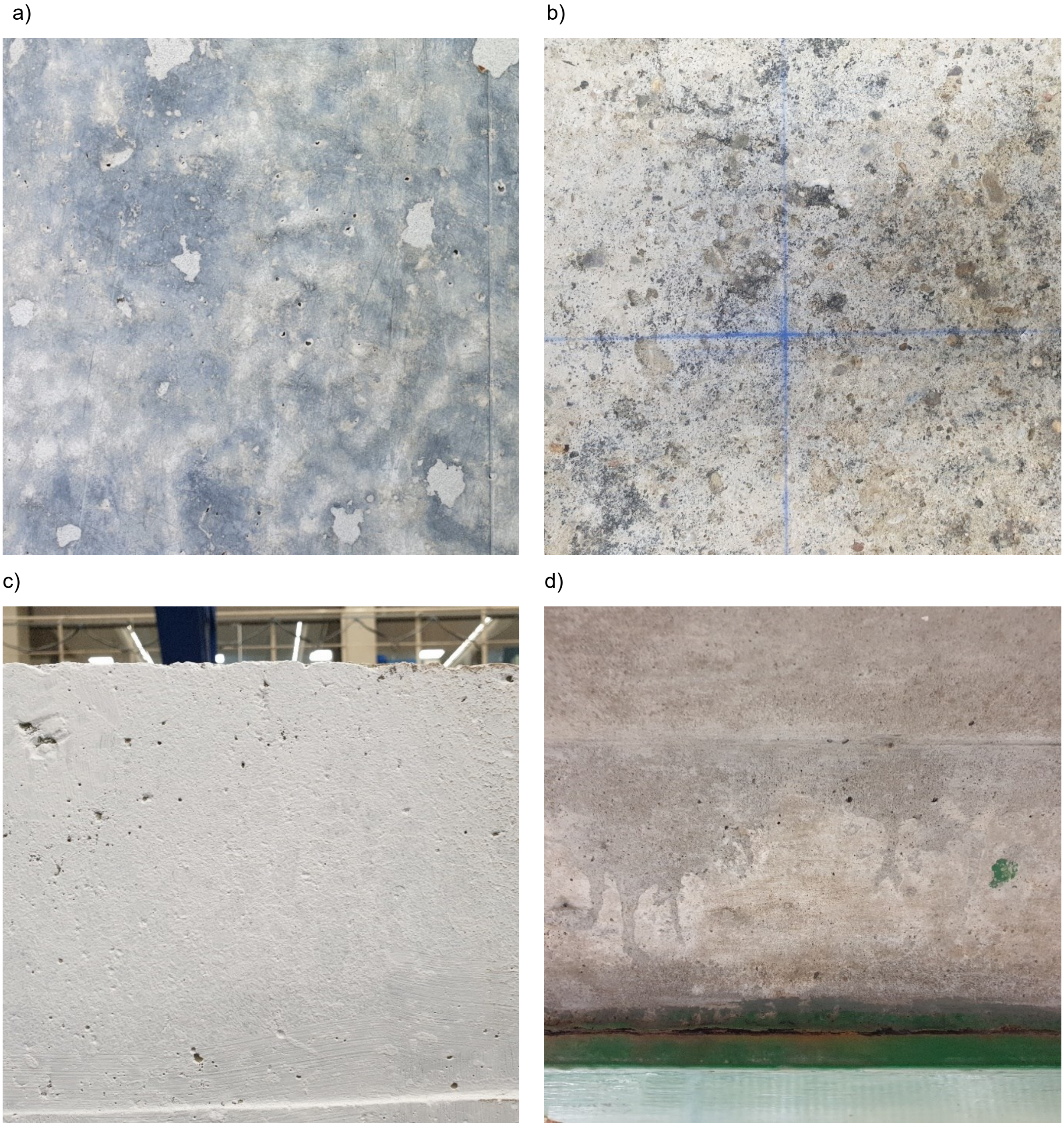

Fig. 8. Concrete surface texture examples: (a) newly built reinforced concrete and formwork marks, (b), spall, (c) white paint, (d) remained coating, (e) efflorescence, (f) algae, (g) crack, dirt and rust stain, (h) steel corrosion and concrete cover damage

3.4 Contamination of parent concrete

The potential contamination of RCA imposes an added challenge for their use given that there might be deleterious pathologies in parent concrete waste streams, such as de-icing salts, sulfate attack, and alkali-silica reaction (ASR). The parent concrete contamination referred to here is related to two aspects, external and internal, as illustrated in Fig. 9.

External contamination of the parent concrete is mainly limited to the concrete cover and, as such, has an insignificant influence on the properties of the RCA. RCA has been shown in several studies to have negligible chloride content (less than 0.01% by mass of aggregate [82, 83]) and water-soluble sulfates below the allowable limit of 1% [71, 83, 84].

The internal presence of critical species such as chloride ions, sulfate ions, or potentially reactive aggregates (Fig. 9.2) overall in the concrete structural member makes the parent concrete decisive for the quality of the RCA [85] and it is of major concern for the quality of RCA. Several studies [86-88] reported reactive RCA, but they were also innocuous to alkali-silica reactions [82]. The extent of reactivity/expansion reached by a concrete member before its demolition will influence the extent of expansion that can be obtained with RCA produced from that concrete member. RCA produced from concretes that have suffered from a high degree of reactivity/expansion/damage can suffer less expansion compared to a similar proportion of unreacted aggregate material of the same origin. This is likely due to the consumption of reactive phases in the RCA; also, it is possible that the residual mortar that surrounds parts of

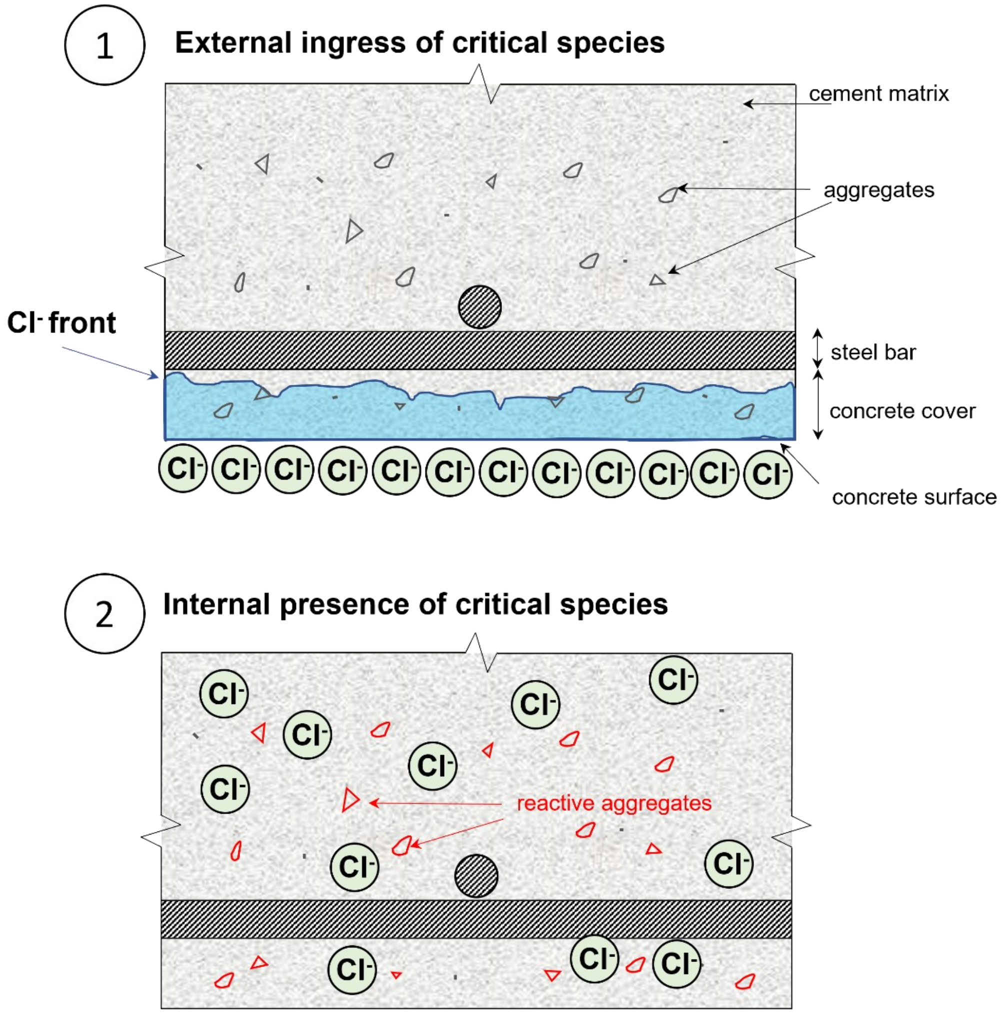

Fig. 9. Contamination of parent concrete caused by 1) external ingress of critical species such as chloride ions being mainly limited to the concrete cover, and 2) internal presence of critical species such as chloride ionsor potentially reactive aggregates overall the concrete structure

reactive particles limits the exposure of the original aggregate to the concrete pore solution, thus reducing further reaction [85]. On the other hand, recycling/crushing of concrete incorporating some reactive aggregate materials can also rejuvenate the reactivity of the original aggregate by exposing reactive silica from fresh aggregate surfaces, thus resulting in a higher expansion of concrete incorporating such RCA compared to “stabilized” original gravel material [85].

To ensure that RCA are not a potential internal source of contaminants for new concrete, selective demolition is required. It would also decrease the number of tests that such aggregates need to pass in order to be used in new concrete. according to EN 12620:2002+A1:2008.

3.5 Characteristic quality indicators

To enable the use of RCA as European Standard EN 12620:2002+A1:2008 [89]−conforming products, it is necessary to test the parent concrete quality of each concrete member of a structure before demolition. The characteristic quality indicators are crucial for a comparative assessment of various types of concrete. Criteria for selecting characteristic quality indicators for parent concrete testing and sorting were as follows: Literature review in Sections 3.1−3.4 and relevance of an indicator to the production and classification of RCA, available techniques to assess certain concrete properties in situ, robustness of the testing, automation capability, process speed, relevance of a quality indicator to a recycler. Quality indicators that are technically feasible to be assessed on concrete structures before demolition are surface visual inspection for deterioration and measurement of parent concrete strength and composition. These are three key characteristic quality indicators that can be linked to properties of RCA and their production, such as energy consumption during crushing, strength and type of cement and aggregates used in parent concrete, and potential alkali silica reactivity. The properties of parent concrete help determine which parts of the concrete structure can be recycled together and which parts should be kept separate to obtain concrete batches of known and consistent quality.

4 Workflow toward more rational concrete waste management

Selective demolition of concrete structures should involve a detailed plan and a workflow. The specific workflow is presented on an example of the concrete bridge in Fig. 10, where different parts of the bridge are sorted using characteristic quality indicators and the concrete is characterized before it is demolished and recycled. Recyclers can have the opportunity to select concrete with properties that best suit their crushing technology and business model. After recycling concrete members of known origin and quality, an advanced classification of recycled materials can be made in separate stockpiles: recycled concrete aggregates from high-strength concrete without contamination (stockpile 1), recycled concrete aggregates from normal-strength concrete without contamination (stockpile 2), recycled concrete aggregates from lightweight aggregate concrete (stockpile 3) without contamination, and others (recycled concrete aggregates from contaminated concrete). Finally, the individual stockpiles will benefit the concrete producers, as their origin and quality will be known upon delivery. For efficient concrete sorting, testing of parent concrete quality would be essential. The following section presents guideline for non-destructive testing of concrete properties which are critical for concrete sorting before demolition.

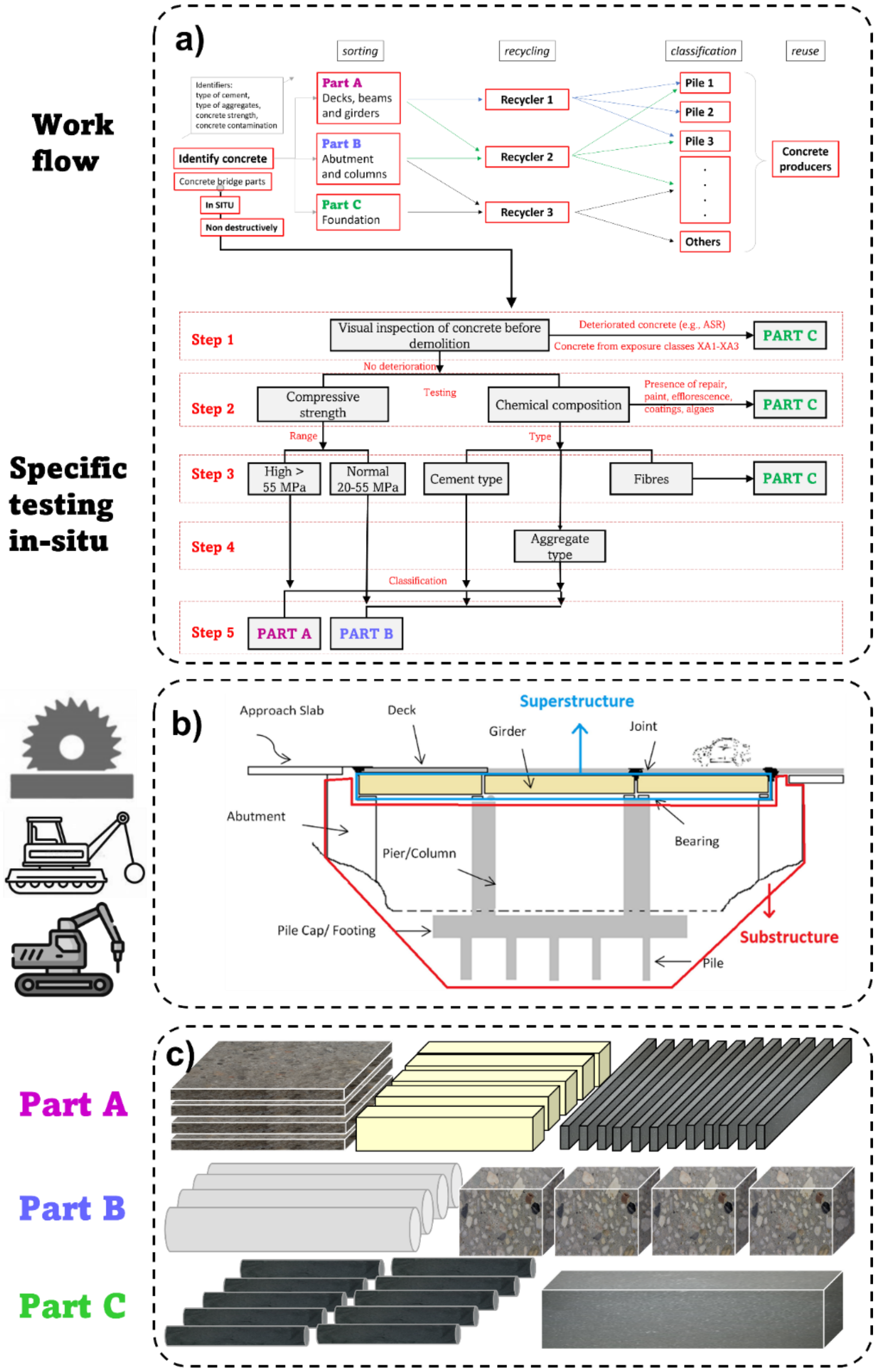

Fig. 10a) Workflow to implement in demolition projects, including specific in-situ testing and classification of concrete members based on strength and composition, b) an example of concrete bridge parts, c) their sorting prior to recycling and classification of concrete members based on a), (Bridge drawing adopted from [90])

5 In-situ testing of concrete properties

5.1 Compressive strength of concrete

The destructive testing requires the extraction of a concrete sample from the structure, which is then analysed in a laboratory. The extraction of such samples tends to be laborious and time consuming. Compared with destructive testing, non-destructive testing offers a promising way towards strength assessment since many non-destructive testing parameters are sensitive to material strength variations [91], and non-destructive testing can be deployed at many locations in real time at construction sites [92, 93]. The rebound hammer and ultrasonic pulse velocity tests are the most commonly used non-destructive methods for in situ concrete strength evaluation. The review of factors affecting the reliability of assessing the concrete strength by rebound hammer and cores [94] outlined the following sources of uncertainty: measurement uncertainties [95], strength variability [96], model uncertainties [96], statistical uncertainties of sampling [97], and influence of uncontrolled factors such as concrete degree of saturation and carbonation [91, 98, 99]. The standard EN 12504-2:2021 [100] specifies the method for determining the rebound index, whereas EN 12504-4:2021 [101] specifies the method for determining the ultrasonic pulse velocity, and EN 13791:2019 [99] summarizes guidance for the assessment of the in situ concrete compressive strength in structures. RILEM TC249-ISC also provides recommendations on non-destructive in situ strength assessment of concrete [102, 103]. It is generally stated that the rebound hardness tests of concrete are not intended as an alternative to the compressive strength testing, but with suitable correlation, they can provide an estimate of the in situ strength, which may be sufficient for the purpose of selective demolition. Nevertheless, in the case of selective demolition, non-destructive strength measurements can be verified, i.e., calibrated with results obtained on a discrete number of samples (cores) taken from the structure and tested in the laboratory, which is a common practice. Since the advantages and disadvantages of concrete strength evaluation in situ are well documented in the literature, standards, and guidelines, the present paper is dedicated to a review of methods that can evaluate concrete chemical composition and contamination.

5.2 Concrete chemical composition and contamination assessment

For determining the chemical composition and contamination type of concrete, only a few methods are available. Most of these techniques are destructive, requiring the extraction of a concrete sample from the structure, which is then analysed in a laboratory for mineralogical composition [104] with optical and electron microscopes. The extraction of such samples tends to be laborious and time-consuming. In the next paragraphs, the non-destructive testing methods are presented.

5.2.1 Visual inspection of concrete surface

Visual inspection is one of the most useful and versatile non-destructive techniques, and it is normally undertaken at the initial phase when assessing concrete deterioration by fire and alkali silica reaction. In spite of visual inspection being simple in principle, it may provide core information about the condition of the deteriorated structure and act as a basis upon which subsequent assessment methods can be performed [105]. Visually apparent deterioration induced by heating includes spalling, cracking, surface crazing, deflection, colour changes, and smoke deterioration; attack by acids and alkalis includes exposed cement paste completely disintegrating together with any calcareous aggregate; ASR includes, among others, cracks (map cracking) and secondary deposits of alkali-silica gel that may appear on the outer concrete surface [106]. These indicators of deteriorated concrete can be assessed visually and further assessed using more advanced methods. A visual inspection of a concrete surface can lead to the immediate classification of a concrete member due to characteristic signs of concrete deterioration. This can be the first line of concrete quality assessment. In the case of non-deteriorated concrete, it is necessary to employ element-characterization techniques for the determination of the chemical composition of the concrete to assess its classification and future application of RCA.

5.2.2 Analysis of concrete composition with a handheld X-Ray Fluorescence Analyzer

State-of-the art techniques relevant to in-situ measurements for determining the material element composition non-destructively, are handheld laser-induced breakdown spectroscopy (hLIBS) and handheld X-Ray fluorescence (hXRF) analyzers. In general, a single LIBS spectrum can be obtained in a fraction of a second, whereas typically tens of seconds to minutes are needed to acquire an XRF spectrum [107]. However, XRF is a non-destructive technique, whereas LIBS is micro-destructive, as each laser shot removes a few nanograms of material from the sample surface, forming a surface crater. Thus, a LIBS analysis of a particular spot on a sample cannot be repeated and cannot be compared to other techniques, which represents a drawback for LIBS [107]. In laboratories, conventional desktop XRF has been one of the most widely used spectroscopic methods for testing the element composition of materials for decades. The hXRF brought a large revolution to the field of chemical materials characterization. Based on previous experience with concrete bulk composition testing with desktop XRF, the hXRF is particularly promising for studying concrete composition in situ. In the field of concrete science, typical desktop XRF is widely applied for the characterization of raw materials used for concrete production, including RCA in powder form. Moreover, the standard EN 196-2: 2014 [108] presents XRF as a method for cement composition testing in laboratories.

The hXRF possesses many advantages, including easy of use, non-destructive testing, the portability (for fieldwork), fast results, large numbers of analysed spots, satisfactory accuracy, and precision [109]. It therefore has a wide application foreground in material science, such as rocks, ores, metals, soil, ceramics, manufactured glass, geoarchaeology, art, and paintings [110-114]. A recent study [115] has shown promising results regarding in situ versus laboratory characterization of historical structures in marine environments using hXRF. hXRF-based methods have been used for the in situ characterization of concrete pavements [116], concrete from nuclear material processing, and liquid waste systems [117]. hXRF readings can also be used to estimate the percentages of sand, silt, and clay in the soil [118].

Fig. 11 shows the working mechanism. An hXRF analyser includes an X-ray source, which irradiates the sample, and an X-ray detector, for detecting the X-ray fluorescence emitted by the sample in response to the irradiation. Each element in the sample emits X-ray fluorescence in energy bands that are characteristic of the element. The detected X-ray fluorescence is analysed to find the energies, or equivalently, the wavelengths of the detected photons, and the qualitative and/or quantitative composition of the sample is determined based on this analysis [119]. A mixture of elements irradiated by a sufficiently energetic X-ray beam absorbs the incident X-rays and re-emits other X-rays, the wavelengths of which are characteristic of the elements in the sample, and the intensities of which may be correlated with their concentrations [120]. Elements from magnesium to uranium are within the detection limit and can be analysed [121]. The device is equipped with a small screen that shows the results instantly, once the device is calibrated for the specific materials (Fig. 12). The measurement times are very short, such that it is possible to collect data for up to 100 samples in a single day [109].

Regarding concrete in situ identification in the context of sorting and selective demolition based on composition, hXRF is believed to be a key solution to this issue owing to its compatibility with lab XRF (Table 2) for concrete characterization, easy installation, maintenance, and large-scale applications. Furthermore, because hXRF can perform non-destructive analysis with minimal sample preparation, it is ideal for in situ concrete structural members. Moreover, hXRF is largely used in the mining and cement industries and can detect a large range of elements characteristic of concrete. However, the hXRF-based method has yet to be studied and applied for determining the chemical element composition of in situ concrete structures. Therefore, hXRF is recommended for a laboratory proof-of-concept to identify and quantify elements in various types of concrete and, therefore, various used cement and aggregate types for the concrete demolition concept. In comparison to destructive, time-consuming, and relatively expensive techniques for concrete characterization in situ, hXRF can be generally applied as a first approach to estimate concrete chemical composition in situ. This would be helpful for ensuring the identification of concrete at the source, improving the demolition efficiency, guiding the quality of recycled concrete, and decreasing the number of standard chemical tests in the laboratory.

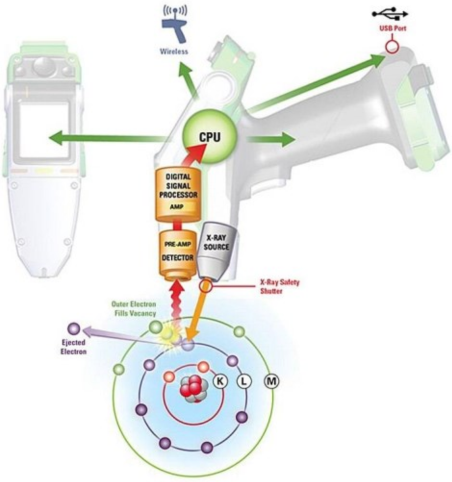

Fig. 11. The X-ray instrument emits energy which changes the electrons orbitals [122]

Fig. 12.The use of hXRF BRUKER device

Table 2. A general comparison between conventional desktop XRF (BRUKER S2 PUMA Series 2) and BRUKER Handheld XRF (S1 TITAN 800) instrument settings

Settings	Conventional desktop XRF (S2 PUMA Series 2)	Handheld XRF (S1 TITAN 800)
Range of detectable elements	Na–Am C–Am with light element (LE) detector	Mg–U
X-Ray tube Anode	Pd or Ag anode	Rh anode
Excitation source	4000 W (50 kV, 2000μA)	4W (50 kV, 200 μA)
X-ray beam path	Vacuum, Air, Helium, Nitrogen	Air (1 bar)
Spot size	1–34 mm	3–8 mm
Filter	10–position automatic filter changer	5–position automatic filter changer
Sample type	Loose powders, granules, solids, pressed pellets, fused beads, and liquids	Loose powders, granules, solids, pressed pellets, fused beads
Sample preparation	Drying	No preparation needed
Scan duration	6–30 s	30 s –10 min
Working distance	contact measurement	contact measurement

6 Further research on hXRF for concrete

6.1 Parameters affecting measurements

There are several influential parameters that need attention for hXRF measurements:

- Distinction between cement and aggregates.

Because the spot size of the hXRF aperture varies between 3 and 8 mm depending on the device, the heterogeneity of the tested material can have a significant impact on the results [121]. When testing the chemical composition of hardened concrete, the challenge lies in recognizing cement paste, fine and coarse aggregates due to partial overlap in particle size distribution and, in some cases, similar element oxides.

Kreijger [123] showed that the skin of a concrete structure consists of three layers, the cement skin (~0.1 mm thick), the mortar skin (~5 mm) and the concrete skin (~30 mm), as shown in Fig. 13. Therefore, it is hypothesized that testing the chemical composition of the surface (first concrete skin layer) will represent the cement type, while testing the chemical composition of the inner layers will yield aggregate types in a relatively homogeneous environmental setting and therefore can be predicted from the direct element readings of hXRF.

- X-ray beam path, air versus vacuum.

Conventional XRF works in a vacuum, while hXRF operates in air. The question is, what effect does air have on hXRF measurements when compared to measurements in vacuum? A Bruker S1-Titan 600 hXRF analyser with a patented compact collimating device [124] has been used for evaluation of the effect of environmental interferences (specifically in the low energy range up to 10 keV) on the graphite, copper, SiO_2 powder, and UO_2. First, the authors used Monte Carlo simulation to calculate the relative intensity of X-ray energy on the surface in both vacuum and air [125]. The former represents the X-rays immediately after emission from the Rh target, while the latter represents reflection of the X-rays by air between the hXRF and the contact surface of the sample. At higher energy levels hardly any difference can be seen (Fig. 14). Second, in the case of graphite, the effect of the environmental interferences was evaluated to be about 20% on the conformity of the measured and simulated results, while those for copper, SiO_2, and UO_2 were about 1%, 3%, and less than 1%, respectively. These results indicate that samples having elements with higher rates of photoelectric absorption followed by fluorescence compared to scattering tend to decrease the effect of the environmental interferences over the entire spectrum.

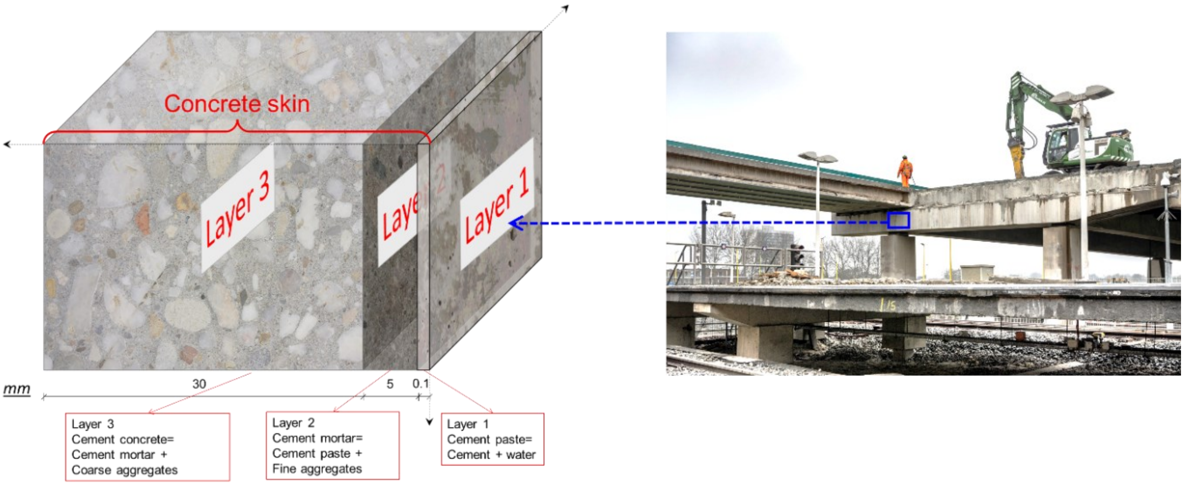

Fig. 13. Characterization of the concrete skin. Credits go to Rijkswaterstaat for the photo of the concrete structure on the right

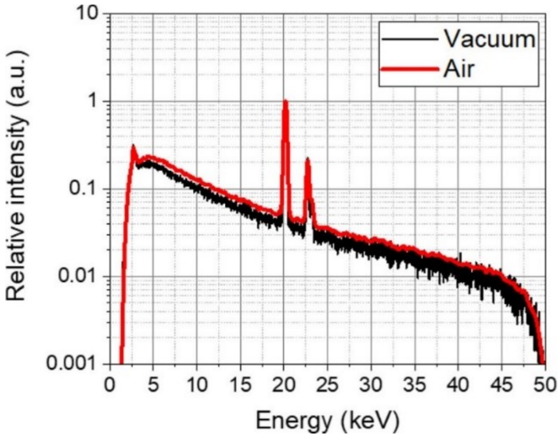

Fig. 14. Monte Carlo N-Particle Transport 6 (MCNP6) simulation of a primary X-ray beam source profile in vacuum and air media [125]. The accelerating voltage is 50 kV

- Filters

hXRF has the possibility of using multiple filters. Filters are used to reduce the intensity of interfering lines and background, and hence improve the signal-to-noise ratio. Normally, background scatter is lower in the vacuum condition, which significantly improves resolution. Filters are placed between the source and the sample (Fig. 15). Commonly used filter materials are aluminium and brass with a thickness between 100 and 1000 µm, depending on the tube lines that have to be filtered out. Fig. 16 shows the effect of different filters implemented in the M4 TORNADO ED-XRF spectrometer on the chemical composition of a historical mortar [115]. The signal on the cementitious mortar was best when no filter was used. This should be considered when testing concrete surfaces.

- Sample preparation.

It is common practice to analyse powders with a conventional desktop XRF analyser. Powdering is a good way to counter mineralogical heterogeneity and is the main justification for sample preparation. If solid flat surfaces are used in geoarchaeology and tested with hXRF, the difference between those and the powdered samples is within counting errors, but not for some heavy elements such as Ti and Fe [109]. In general, there is no gain in instrumental precision by analysing powders instead of unprepared rock cores [127].

Among the correctible elements, three groups can be proposed with regards to the accuracy of hXRF measurements on rock cores versus powders: the elements or oxides better determined on rock cores, those better determined on powders, and those that show similar results (Fig. 17) [127].This suggests that when measuring concrete surface composition, powdering should be investigated to demonstrate whether the testing of solid surface and powdered surface provides similar results and whether all concrete elements are acceptable in both media.

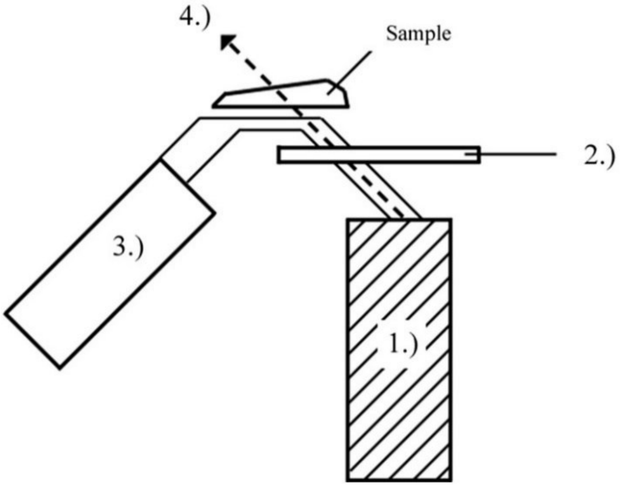

Fig. 15. Scheme of hXRF, including: (1) X-ray source (rhodium tube); (2) filter (6 mil Cu, 1 mil Ti, 12 mil Al); (3) detector; as well as (4) beam path at 45°angle, adopted from [126]

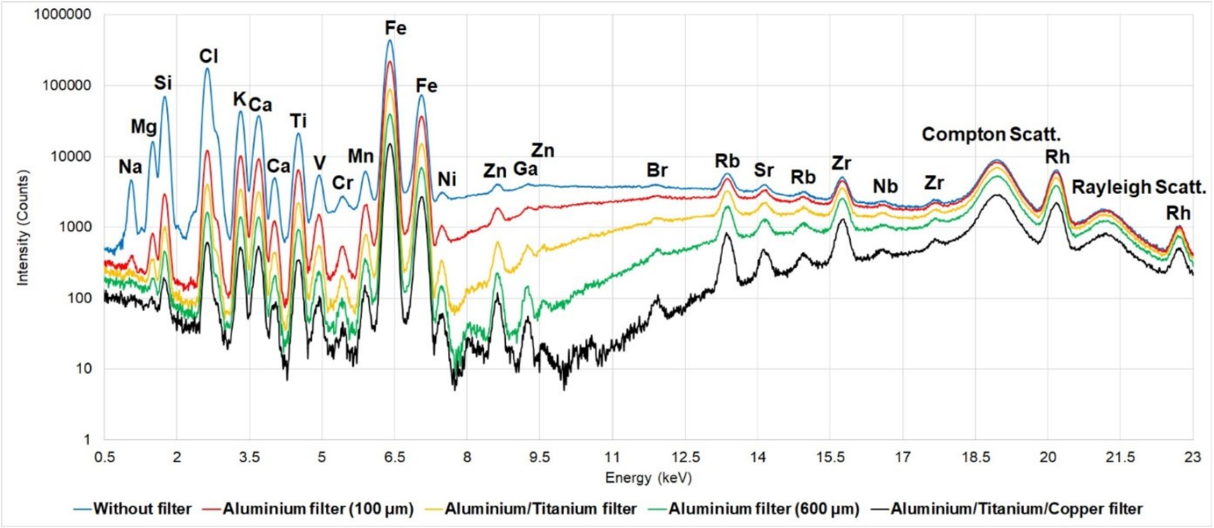

Fig. 16. A comparison of detection power using different filters implemented in the M4 TORNADO ED-XRF spectrometer applied to a historical mortar as an example of signal improvement [115]

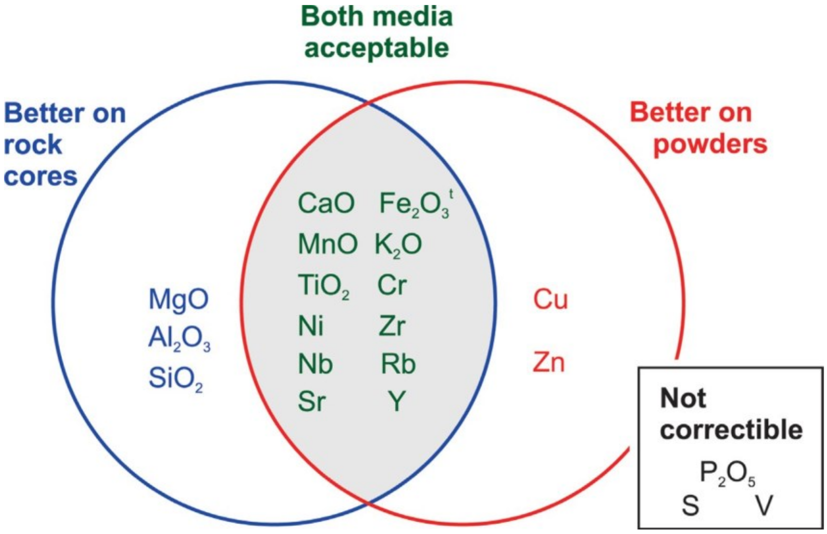

Fig. 17. ***A** Venn diagram represents the three groups of correctible elements: (1) elements better determined in situ on rock cores with respect to accuracy, (2) elements better determined on powders and (3) elements showing similar results regardless of the media. The diagram also shows the elements that are detected but not correctable. The following elements and oxides are determined in mining plus mode for best results: Al_2O_3, CaO, Fe_2O_3, MgO, MnO, Ni, SiO_2, and Zr. The following elements and oxides are determined in soil mode for best results: Cr, K_2O, Nb, Rb, Sb, TiO_2 and Y. Adopted from [127]*

- Concrete surface roughness.

Surface irregularities (e.g., pores, voids, cracks) on rough surfaces or in the middle layers of concrete (Figs. 18, 19) have the potential to store measurements. Particularly, moisture and air are retained in these irregularities. Thus, attention should be given to the sample preparation to find the optimal surface roughness and moisture for the contacting surfaces to achieve optimal performance of the hXRF measurements (avoiding air gaps and contact with water). Pretreatments such as grinding and polishing, significantly smooth the concrete surface, but they also may create different micrometer-sized irregularities. Thus, grinding, even if performed carefully, creates various irregularities of different shapes (such as scratches) that are produced by the abrasive particles in the grinding paper. The homogeneity of the microstructure, the level of purity, the size and distribution of aggregate particles, and other hard constituents (e.g., fibres) in the concrete matrix are the parameters that may influence the results.

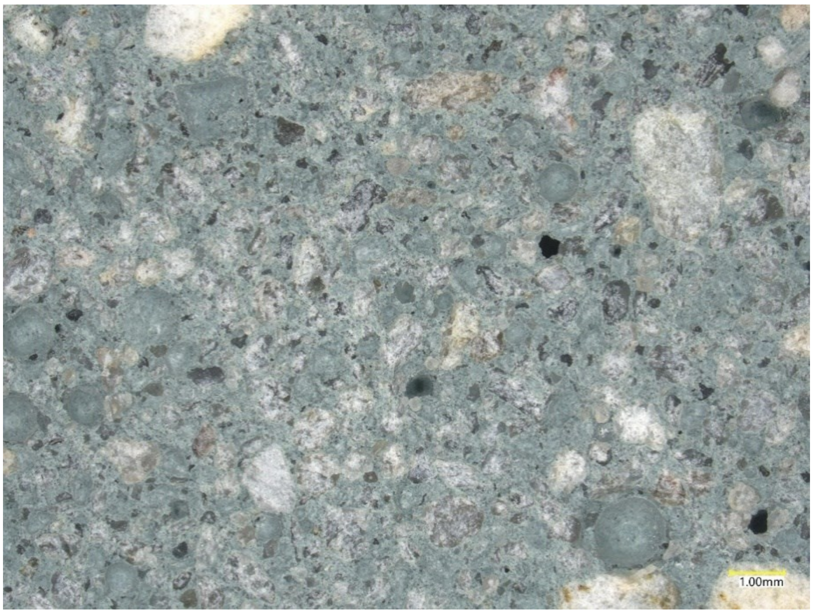

Fig. 18. Concrete middle section topography (measured by focus variation microscopy 20×, lateral resolution: 2 µm, vertical resolution: 50 nm)

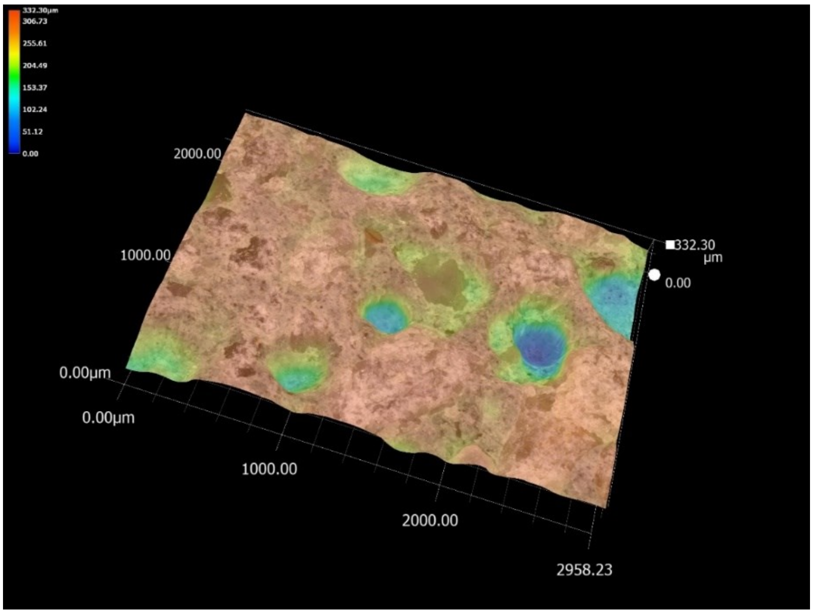

Fig. 19. Three-dimensional height profiles of the concrete middle section (concrete middle section appearance is presented in Fig. 18.)

- Low concentration elements detection.

Regarding concrete contamination such as Cl and S, for their largely lower concentrations compared to, for instance, CaO or SiO_2, a hXRF instrument may incorporate a calcium or lead-anode X-ray tube such as that used by Cesareo et al. [128] to determine Cl and S in frescoes and stone monuments. The detection limits were reported to be 0.04% m/m for Cl and 0.03% m/m for S.

- Validation techniques.

Petrography and the method of extracting elements with acids and then analyzing them with the inductively coupled plasma (ICP) technique are two destructive methods that can be used to study the composition of concrete. In addition, conventional XRF and Energy-dispersive X-ray Spectroscopy (EDS) may be used for the validation of hXRF results.

6.2 Algorithms to automate the characterization and selective demolition of concrete structures

With the rapid advances in data science concerning the easier manipulation of large datasets (big data), the development of machine learning regression models, the increasing use of building information modelling (BIM), digital twins, and the Internet of Things (IoT), significant benefits can be gained by the application of these methods to automating the characterization of concrete as well as the selective demolition of structures.

For instance, an advanced terrestrial laser scanning (TLS)‑based method automates the classification of rebar diameters using machine learning in order to enable accurate rebar spacing inspection [129]. In this method, a new methodology named Density based Modelling (DBM) is proposed to improve classification accuracy. Experimental tests on laboratory specimens with rebars of seven different diameters (D10‑D40) were conducted, and the results show that the prediction accuracy for the large rebar diameter group (D25‑D40) was up to 97.2%. However, it was found that its performance in predicting small rebar diameter groups (D10-D20) is much lower ‑ around 56.0% [129].

Using data from both ground-penetrating radar (GPR) and electromagnetic induction (EMI), [130] a strategy based on deep learning is used to figure out the cover thickness and diameter of steel bars in reinforced concrete structures. The proposed framework is made up of two parts: 1) finding hyperbolic signals in radargrams, and 2) figuring out the diameter of reinforcement bars and the thickness of the cover.

Non-destructive detection of steel reinforcement corrosion in concrete structures has been achieved using techniques such as ground penetrating radar [131]. Current inspection practices require a large amount of time for inspection and can pose a safety risk to inspectors. These drawbacks could be overcome by using ground robotic systems [131]. Furthermore, work is being conducted on the enrichment of Industry Foundation Classes (IFC) in BIM with data on damage and deterioration [132].

Finally, such technologies should preferably lead to BIM-based frameworks and databanks of material stock for reusing recycled materials and entire structural members [133]. Efforts are already under way to develop BIM models of high level of development (LOD) enriched with data on the static, mechanical, and reuse properties of the built materials and members. From such models merged with LCA and multi-criteria decision-making tools and embedded in city-wide platforms of building stock data, the concepts of „design from stock“ and „design with stock“ can successfully emerge [133] leading to a fully circular construction industry.

7 Conclusions

The various recycling technologies for concrete waste have greatly contributed to increasing the sustainability of waste management. However, mixed concrete streams are becoming more prevalent, and the quality of RCA is uncertain. Advanced solutions for recycling technology cannot address the quality issues of input concrete waste.

Therefore, a new workflow toward a more rational CDW management and the selective demolition of concrete structures in relation to concrete type characterization, is presented in this paper. Knowing the origin of RCA should aid in improving predictions of the impact of their use on the properties of new concrete by separating aggregate stockpiles based on parent concrete properties.

This paper proposes a specific workflow to be implemented in demolition projects for parent concrete origin and quality identification before concrete structure demolition. Compressive strength, chemical composition, and contamination are selected for characteristic quality indicators and concrete classification. Parent concrete strength determines the physical and mechanical properties of RCA, such as energy of crushing and strength. The parent concrete composition can ensure that RCA have the appropriate application (aggregates, mineral addition for clinker manufacturing, pozzolanic material, filler). Contamination evaluation can ensure that the contaminated concrete is kept apart. Non-destructive testing methods are proposed to estimate the quality of the concrete before demolition. A hXRF analyser could potentially be used for concrete composition measurements in situ.hXRF should be considered a preliminary screening tool for concrete quality selection and not a substitute for conventional chemical methods (e.g., desktop XRF, fusion ICP-ES and ICP-MS). The hXRF possesses many advantages, including non-destructive testing, large numbers of analysed spots, high sensitivity, compatibility with lab techniques for material characterization, and easy installation and maintenance. Further research is dedicated to the laboratory proof of a proposed characterization approach for concrete quality assessment.

Considering the above presented evidence, it can be concluded that the practical application of non-destructive concrete characterization for the purposes of selective demolition can significantly increase the sustainability of the construction industry, unlocking a huge potential for optimized material recovery and reuse and contributing greatly to a fully circular construction sector.

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References

[1] Global Material Resources Outlook to 2060 Economic Drivers and Environmental Consequences,(2019) OECD publishing.

[2] M. Longo, A. Sánchez Rodríguez, Á. S. López Marroquín, A. J. Domínguez, Ó. Bouzas Rodríguez, P. Sanecka, C. Marchiori, M. Rigotti, Review of methodologies and instruments for diagnostics of transport infrastructure, IM-SAFE-Project (2022).

[3] P. V. Sáez, M. Osmani, A diagnosis of construction and demolition waste generation and recovery practice in the European Union, J. Cleaner Prod. 241 (2019), 118400. 10.1016/j.jclepro.2019.118400

[4] G. Cai, D. Waldmann, A material and component bank to facilitate material recycling and component reuse for a sustainable construction: Concept and preliminary study. Clean Technol. Environ. Policy 21(10) (2019) 2015-2032. 10.1007/s10098-019-01758-1

[5] J. L. Gálvez-Martos, D. Styles, H. Schoenberger, B. Zeschmar-Lahl, Construction and demolition waste best management practice in Europe. Resour. Conserv. Recycl. 136 (2018)166-178. 10.1016/j.resconrec.2018.04.016

[6] C. Zhang, M. Hu, X. Yang, B. Miranda-Xicotencatl, B. Sprecher, F. Di Maio, X. Zhong, A. Tukker, Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands, J. Cleaner Prod. 266 (2020) 121718. 10.1016/j.jclepro.2020.121718

[7] M.H. Faber, Risk and safety in civil engineering, 2007.

[8] P. Bazant, Q. Yu, G. H. Li, Excessive long-time deflections of prestressed box girders. I: Record-span bridge in Palau and other paradigms, J. Struct. Eng. ASCE 138(6) (2012). 10.1061/(ASCE)ST.1943-541X.0000487

[9] RWS Grote Projecten en Onderhoud, Sloopoorzaken bruggen en viaducten in en over rijkswegen, Iv-Infra b.v. 2016.

[10] A1: vervanging viaduct Hoog Burel. Available from: https://www.rijkswaterstaat.nl/wegen/projectenoverzicht/a1-vervanging-viaduct-hoog-burel.

[11] F.Tomosawa, T.Noguchi, M.Tamura, The way concrete recycling should be,J. Adv. Concr. Technol. 3(1)(2005) 3-16.https://doi.org/10.3151/jact.3.3

[12] European Commission, 'Com/2020/98 Final - Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions: A New Circular Economy Action Plan for a Cleaner and More Competitive Europe', (2020).

[13] EU-DIRECTIVE-2008/98/EC of the European Parliament and the Council of 19 November 2008 on Waste and Repealing Certain Directives, Official Journal of the European Union, 2008.

[14] EU-DIRECTIVE-2018/851/EC of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste, European Union: Official Journal of the European Union, 2018.

[15] Ecorys, EU Construction & Demolition Waste Management Protocol. 2016, European Commission Brussels, Belgium.

[16] Commission, E., Guidelines for the Waste Audits before Demolition and Renovation Works of Buildings. 2018, European Commission Brussels, Belgium.

[17] E.Khoury, W.Ambrós, B.Cazacliu, C. H.Sampaio, S. Remond, Heterogeneity of recycled concrete aggregates, an intrinsic variability, Constr. Build. Mater. 175 (2018) 705-713.https://doi.org/10.1016/j.conbuildmat.2018.04.163

[18] M.Pepe, T. M.Grabois, M. A.Silva, L. M.Tavares, R. D.Toledo Filho, Mechanical behaviour of coarse, lightweight, recycled and natural aggregates for concrete, Proceedings of the Institution of Civil Engineers-Construction Materials, 173(2)(2020) 70-78.https://doi.org/10.1680/jcoma.17.00081.

[19] N.Tošić, S.Marinković, I.Ignjatović, A database on flexural and shear strength of reinforced recycled aggregate concrete beams and comparison to Eurocode 2 predictions,Constr. Build. Mater. 127 (2016) 932-944.https://doi.org/10.1016/j.conbuildmat.2016.10.058

[20] M. Nedeljković, J. Visser, B. Šavija, S. Valcke, E. Schlangen, Use of fine recycled concrete aggregates in concrete: A critical review, J. Build. Eng. 38 (2021) 102196. 10.1016/j.jobe.2021.102196.

[21] J. Pacheco, J. de Brito, Recycled Aggregates Produced from Construction and Demolition Waste for Structural Concrete: Constituents, Properties and Production, Materials, 14(19) (2021) 5748. 10.3390/ma14195748

[22] N. Roussat, C. Dujet, J. Méhu, Choosing a sustainable demolition waste management strategy using multicriteria decision analysis, Waste Manage. 29(1) (2009)12-20. 10.1016/j.wasman.2008.04.010.

[23] https://zenrobotics.com/solutions/heavy-picker/#.

[24] M. Alexander and S. Mindess, Aggregates in concrete (Modern concrete technology) 2005, Spon Press, London.

[25] M. V. A. Florea, H. J. H. Brouwers, Properties of various size fractions of crushed concrete related to process conditions and re-use, Cem. Concr. Res. 52 (2013) 11-21. 10.1016/j.cemconres.2013.05.005.

[26] K.J. Schenk, Patent No. WO 2011/142663 (2011), The Netherlands.

[27] S. Lotfi, J. Deja, P. Rem, R. Mróz, E. van Roekel, H. van der Stelt, Mechanical recycling of EOL concrete into high-grade aggregates, Resour. Conserv. Recycl. 87 (2014) 117-125. 10.1016/j.resconrec.2014.03.010.

[28] M. Quattrone, S. C. Angulo, V. M. John, Energy and CO2 from high performance recycled aggregate production, Resour. Conserv. Recycl., 90 (2014) 21-33. 10.1016/j.resconrec.2014.06.003.

[29] N. Tošić, , J. M. Torrenti, T. Sedran, I. Ignjatović, Toward a codified design of recycled aggregate concrete structures: Background for the new fib Model Code 2020 and Eurocode 2, Structural Concrete, 22(5) (2021) 2916-2938. https://doi.org/10.1002/suco.202000512.

[30] C.F.Hendriks and H. Pietersen, Report 22: SUSTAINABLE raw materials: construction and demolition waste–state-of-the-art report of RILEM technical committee 165-SRM. Vol. 22. 2000: RILEM publications.

[31] A. Di Maria, J. Eyckmans, K. Van Acker, Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making, Waste Manage. 75 (2018), 3-21.https://doi.org/10.1177/0734242X16657605.

[32] S. H. Ghaffar, M. Burman, N. Braimah. Pathways to circular construction: An integrated management of construction and demolition waste for resource recovery. J. Cleaner Prod., 244 (2020), 118710, 10.1016/j.jclepro.2019.118710

[33] M. Rašković, A. M. Ragossnig, K. Kondracki, M. Ragossnig-Angst, Clean construction and demolition waste material cycles through optimised pre-demolition waste audit documentation: A review on building material assessment tools,Waste Manage. Res.38(9) (2020) 923-941. https://doi.org/10.1177/0734242X209367.

[34] R. V. Silva, J. De Brito, R. K. Dhir, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production, Constr. Build. Mater. 65(2014)201-217. 10.1016/j.conbuildmat.2014.04.117

[35] S. C. Kou, C. S. Poon, Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete, Constr. Build. Mater.77 (2015) 501-508, 10.1016/j.conbuildmat.2014.12.035

[36] M.Nedeljković,A.Mylonas, V.Wiktor,E.Schlangen, J.Visser, Influence of sand drying and mixing sequence on the performance of mortars with fine recycled concrete aggregates, Constr. Build. Mater. 315(2022) 125750.https://doi.org/10.1016/j.conbuildmat.2021.125750.

[37] A.Mylonas, Experimental investigation of concrete mixtures incorporating recycled concrete aggregates, MSc thesis (2021) Delft University of Technology, The Netherlands.http://resolver.tudelft.nl/uuid:e0075d76-d0c9-4425-8214-9317303e8721.

[38] D.Carro-López, B.González-Fonteboa, J.De Brito, F.Martínez-Abella, I.González-Taboada,P.Silva, Study of the rheology of self-compacting concrete with fine recycled concrete aggregates,Constr. Build. Mater. 96 (2015) 491-501.https://doi.org/10.1016/j.conbuildmat.2015.08.091

[39] S. C.Kou, C. S.Poon, Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates,Cem. Concr. Compos.31(9)(2009) 622-627.https://doi.org/10.1016/j.cemconcomp.2009.06.005

[40] I. S.Ignjatović, S. B. Marinković, N.Tošić, Shear behaviour of recycled aggregate concrete beams with and without shear reinforcement, Eng. Struct.141(2017)386-401.https://doi.org/10.1016/j.engstruct.2017.03.026.

[41] D.Pedro, J.De Brito, L. Evangelista, Influence of the use of recycled concrete aggregates from different sources on structural concrete,Constr. Build. Mater. 71 (2014)141-151.https://doi.org/10.1016/j.conbuildmat.2014.08.030

[42] S.Lotfi, C2CA Concrete Recycling Process, PhD thesis (2016) Delft University of Technology, The Netherlands.https://doi.org/10.4233/uuid:70505a1f-c0d7-47c7-ab62-8d487761c021

[43] G.Andreu,E. Miren, Experimental analysis of properties of high performance recycled aggregate concrete,Constr. Build. Mater.52(2014) 227-235.https://doi.org/10.1016/j.conbuildmat.2013.11.054

[44] N.Tošić, S.Marinković, N.Pecić, I. Ignjatović, J. Dragaš, Long-term behaviour of reinforced beams made with natural or recycled aggregate concrete and high-volume fly ash concrete,Constr. Build. Mater. 176(2018) 344-358.https://doi.org/10.1016/j.conbuildmat.2018.05.002

[45] S. Omary, E. Ghorbel, G. Wardeh, Relationships between recycled concrete aggregates characteristics and recycled aggregates concretes properties, Constr. Build. Mater. 108 (2016) 163-174, 10.1016/j.conbuildmat.2016.01.042.

[46] M.Tavakoli, P.Soroushian, Strengths of recycled aggregate concrete made using field-demolished concrete as aggregate, Materials Journal 93(2) (1996) 178-181.

[47] L.Evangelista, J. De Brito, Mechanical behaviour of concrete made with fine recycled concrete aggregates,Cem. Concr. Compos. 29(5)(2007) 397-401.https://doi.org/10.1016/j.cemconcomp.2006.12.004

[48] S.Levy, P. Helène, Durability of concrete mixed with fine recycled aggregates, Exacta, 5(1) (2007) 25-34.

[49] H.Yaprak, H. Y.Aruntas, I.Demir, O.Simsek, G.Durmus, Effects of the fine recycled concrete aggregates on the concrete properties. International Journal of Physical Sciences, 6(10)(2011) 2455-2461.https://doi.org/10.5897/IJPS11.253.

[50] P. Pereira, L. Evangelista, J. De Brito, The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates, Constr. Build. Mater. 28(1) (2012) 722-729. https://doi.org/10.1016/j.conbuildmat.2011.10.050.

[51] A. G. Khoshkenari, P. Shafigh, M. Moghimi, H. B. Mahmud, The role of 0–2 mm fine recycled concrete aggregate on the compressive and splitting tensile strengths of recycled concrete aggregate concrete, Mater. Des. 64 (2014) 345-354. https://doi.org/10.1016/j.matdes.2014.07.048.

[52] F. Cartuxo, J. De Brito, L. Evangelista, J. R. Jimenez, E. F. Ledesma, Rheological behaviour of concrete made with fine recycled concrete aggregates–Influence of the superplasticizer, Constr. Build. Mater. 89 (2015) 36-47. https://doi.org/10.1016/j.conbuildmat.2015.03.119.

[53] F. Cartuxo, J. De Brito, L. Evangelista, J. R. Jiménez, E. F. Ledesma,Increased durability of concrete made with fine recycled concrete aggregates using superplasticizers, Materials, 9(2) (2016) 98.https://doi.org/10.3390/ma9020098.

[54] J.A.Bogas, J. De Brito, D. Ramos, Freeze–thaw resistance of concrete produced with fine recycled concrete aggregates. J. Cleaner Prod. 115 (2016) 294-306.https://doi.org/10.1016/j.jclepro.2015.12.065.

[55] L. Evangelista, J. De Brito, Flexural behaviour of reinforced concrete beams made with fine recycled concrete aggregates, KSCE J. Civ. Eng. 21(1) (2017) 353-363. https://doi.org/10.1007/s12205-016-0653-8.

[56] L. Evangelista, J. De Brito, Durability of crushed fine recycled aggregate concrete assessed by permeability-related properties, Mag. Concr. Res. (2018) 1-9. https://doi.org/10.1680/jmacr.18.00093.

[57] V.Radonjanin, M.Malešev, S.Marinković, A. E. S.Al Malty, Green recycled aggregate concrete,Constr. Build. Mater. 47(2013) 1503-1511.https://doi.org/10.1016/j.conbuildmat.2013.06.076

[58] J.Thomas, N. N.Thaickavil, P. M.Wilson, Strength and durability of concrete containing recycled concrete aggregates,J. Build. Eng. 19(2018)349-365.https://doi.org/10.1016/j.jobe.2018.05.007.

[59] Y.Geng, Q.Wang, Y. Wang, H.Zhang, Influence of service time of recycled coarse aggregate on the mechanical properties of recycled aggregate concrete. Mater. Struct. 52(5) (2019) 1-16.https://doi.org/10.1617/s11527-019-1395-0.

[60] E. Köken, A. Özarslan, New testing methodology for the quantification of rock crushability: Compressive crushing value (CCV),Int. J. Miner. Metall. Mater.25(11) (2018) 1227-1236, 10.1007/s12613-018-1675-7.

[61] T. Korman, G. Bedekovic, T. Kujundzic, D. Kuhinek, Impact of physical and mechanical properties of rocks on energy consumption of jaw crusher, Physicochem. Probl. Miner. Process. 51(2015). 10.5277/ppmp150208

[62] Y. Zeng, E. Forssberg, Energy consumption in fine crushing and dry rod grinding, Min. Metall. Explor. 9(2) (1992)69-72, 10.1007/BF03402973

[63] H. Krour, R. Trauchessec, A. Lecomte, C. Diliberto, L. Barnes-Davin, B. Bolze, A. Delhay, Incorporation rate of recycled aggregates in cement raw meals, Constr. Build. Mater. 248 (2020) 118217. 10.1016/j.conbuildmat.2020.118217.

[64] J. Schoon, K. De Buysser, I. Van Driessche, N. De Belie, Fines extracted from recycled concrete as alternative raw material for Portland cement clinker production, Cem. Concr. Compos. 58(2015)70-80. 10.1016/j.cemconcomp.2015.01.003

[65] E. Kwon, J. Ahn, B. Cho, D. Park, A study on development of recycled cement made from waste cementitious powder, Constr. Build. Mater. 83 (2015) 174-180. 10.1016/j.conbuildmat.2015.02.086

[66] A. Bordy, A. Younsi, S. Aggoun, B. Fiorio, Cement substitution by a recycled cement paste fine: Role of the residual anhydrous clinker, Constr. Build. Mater.132 (2017)1-8. 10.1016/j.conbuildmat.2016.11.080

[67] G. Bianchini, E. Marrocchino, R. Tassinari, C. Vaccaro, Recycling of construction and demolition waste materials: a chemical–mineralogical appraisal, Waste Manage. 25(2) (2005)149-159. 10.1016/j.wasman.2004.09.005.

[68] K. Kalinowska-Wichrowska, M. Kosior-Kazberuk, E. Pawluczuk, The properties of composites with recycled cement mortar used as a supplementary cementitious material, Materials 13(1) (2019) 64. 10.3390/ma13010064.

[69] M. V. A. Florea, Z. Ning, H. J. H. Brouwers, Activation of liberated concrete fines and their application in mortars, Constr. Build. Mater.50 (2014) 1-12. 10.1016/j.conbuildmat.2013.09.012.

[70] M. Braga, J. de Brito, R. Veiga, Reduction of the cement content in mortars made with fine concrete aggregates, Mater. Struct.47(1) (2014) 171-182. 10.1617/s11527-013-0053-1.

[71] S. C. Angulo, C. Ulsen, V. M. John, H. Kahn, M. A. Cincotto, Chemical–mineralogical characterization of C&D waste recycled aggregates from São Paulo, Brazil, Waste Manage. 29 (2) (2009) 721-730. 10.1016/j.wasman.2008.07.009.

[72] L. Oksri-Nelfia, P. Y. Mahieux, O. Amiri, P. Turcry, J. Lux, Reuse of recycled crushed concrete fines as mineral addition in cementitious materials, Mater. Struct. 49(8) (2016) 3239-3251, 10.1617/s11527-015-0716-1.

[73] Z. Shui, D. Xuan, H. Wan, B. Cao, Rehydration reactivity of recycled mortar from concrete waste experienced to thermal treatment, Constr. Build. Mater. 22(8) (2008)1723-1729, 10.1016/j.conbuildmat.2007.05.012.

[74] Z. Shui, R. Yu, J. Dong, Activation of fly ash with dehydrated cement paste. ACI materials Journal, 108(2) (2011) 204.

[75] M. V. A. Florea, Secondary materials applied in cement-based products: treatment, modelling and environmental interaction. [Phd Thesis 1 (Research TU/e / Graduation TU/e), Built Environment]. Technische Universiteit Eindhoven. https://doi.org/10.6100/IR772902

[76] V. Corinaldesi, G. Moriconi, Influence of mineral additions on the performance of 100% recycled aggregate concrete, Constr. Build. Mater. 23(8) (2009) 2869-2876. 10.1016/j.conbuildmat.2009.02.004

[77] N.Algourdin,P.Pliya,A. L.Beaucour,A.Noumowé, D. di Coste, Effect of fine and coarse recycled aggregates on high-temperature behaviour and residual properties of concrete. Constr. Build. Mater.341(2022) 127847.https://doi.org/10.1016/j.conbuildmat.2022.127847

[78] R. N.Razafinjato, A. L. Beaucour, R. L.Hebert, B.Ledesert, R.Bodet, A.Noumowe, High temperature behaviour of a wide petrographic range of siliceous and calcareous aggregates for concretes,Constr. Build. Mater. 123(2016) 261-273.https://doi.org/10.1016/j.conbuildmat.2016.06.097

[79] Z.Xing, A. L.Beaucour, R.Hebert, A.Noumowe, B.Ledesert, Influence of the nature of aggregates on the behaviour of concrete subjected to elevated temperature,Cem. Concr. Res. 41(4)(2011) 392-402.https://doi.org/10.1016/j.cemconres.2011.01.005.

[80] P. Hüthwohl, I. Brilakis, Detecting healthy concrete surfaces, Adv. Eng. Inf. 37 (2018) 150-162, 10.1016/j.aei.2018.05.004.

[81] T. G. Nijland, J. A. Larbi, Microscopic examination of deteriorated concrete. In Non-destructive evaluation of reinforced concrete structures, 137-179, Woodhead Publishing,(2010). 10.1533/9781845699536.2.137

[82] N. Y. Ho, Y. P. K. Lee, W. F. Lim, T. Zayed, K. C. Chew, G. L. Low, S. K. Ting, Efficient utilization of recycled concrete aggregate in structural concrete, J. Mater. Civ. Eng. 25(3) (2013) 318-327. 10.1061/(ASCE)MT.1943-5533.0000587.

[83] M. Nedeljković, J. Visser, T. G. Nijland, S. Valcke, E. Schlangen, Physical, chemical and mineralogical characterization of Dutch fine recycled concrete aggregates: A comparative study, Constr. Build. Mater. 270 (2021) 121475. 10.1016/j.conbuildmat.2020.121475.

[84] F. Rodrigues, M. T. Carvalho, L. Evangelista, J. De Brito, Physical–chemical and mineralogical characterization of fine aggregates from construction and demolition waste recycling plants, J. Cleaner Prod. 52 (2013) 438-445. 10.1016/j.jclepro.2013.02.023.

[85] S. Beauchemin, B. Fournier, J. Duchesne, Evaluation of the concrete prisms test method for assessing the potential alkali-aggregate reactivity of recycled concrete aggregates, Cem. Concr. Res.104 (2018) 25-36. 10.1016/j.cemconres.2017.10.008

[86] F. Locati, C. Zega, G. C. dos Santos, S. Marfil, D. Falcone, Petrographic method to semi-quantify the content of particles with reactive components and residual mortar in ASR-affected fine recycled concrete aggregates, Cem. Concr. Compos. 119 (2021) 104003. 10.1016/j.cemconcomp.2021.104003

[87] R. Johnson, M. H. Shehata, The efficacy of accelerated test methods to evaluate alkali silica reactivity of recycled concrete aggregates, Constr. Build. Mater. 112 (2016) 518-528. 10.1016/j.conbuildmat.2016.02.155.

[88] M. H. Shehata, C. Christidis, W. Mikhaiel, C. Rogers, M. Lachemi, Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali–silica reaction, Cem. Concr. Res. 40(4) (2010) 575-582. 10.1016/j.cemconres.2009.08.008.

[89] EN 12620:2002+A1:2008 en, in Aggregates for concrete.

[90] B. A. Bektas, A. Carriquiry, O. Smadi. Using classification trees for predicting national bridge inventory condition ratings, J. Infrastruct. Syst. 19(4) (2013) 425-433. 10.1061/(ASCE)IS.1943-555X.0000143

[91] D. Breysse, J. L. Martínez-Fernández, Assessing concrete strength with rebound hammer: review of key issues and ideas for more reliable conclusions, Mater. Struct. 47(9) (2014) 1589-1604. 10.1617/s11527-013-0139-9

[92] S. K. Choi, N. Tareen, J. Kim, S. Park, I. Park, Real-time strength monitoring for concrete structures using EMI technique incorporating with fuzzy logic, Applied Sciences 8(1) (2018) 75. 10.3390/app8010075.

[93] J. W. Kim, C. Lee, S. Park, K. T. Koh, Real-time strength development monitoring for concrete structures using wired and wireless electro-mechanical impedance techniques, KSCE Journal of Civil Engineering, 17(6) (2013) 1432-1436. 10.1007/s12205-013-0390-1.

[94] M. Alwash, D. Breysse, Z. M. Sbartaï, K. Szilágyi, A. Borosnyói, Factors affecting the reliability of assessing the concrete strength by rebound hammer and cores, Constr. Build. Mater. 140 (2017) 354-363. 10.1016/j.conbuildmat.2017.02.129.

[95] K. Szilágyi, A. Borosnyói, I. Zsigovics, Extensive statistical analysis of the variability of concrete rebound hardness based on a large database of 60 years experience, Constr. Build. Mater. 53 (2014) 333-347. 10.1016/j.conbuildmat.2013.11.113

[96] N.J. Carino, Nondestructive testing of concrete: History and challenges. In. Lee, George C, ed; Chang, K. C, ed. Proceedings of the International Workshop on Civil Infrastructure Systems: Application of intelligent systems and advanced materials on bridge systems. Taipei, U.S. National Center for Earthquake Engineering Research (1994) 343-99.

[97] N. Pereira, X. Romão, Assessment of the concrete strength in existing buildings using a finite population approach, Constr. Build. Mater. 110 (2016)106-116. 10.1016/j.conbuildmat.2016.02.021

[98] Recommendations for Testing Concrete by Hardness Methods. 1984, RILEM.

[99] EN 13791 Assessment of in-situ compressive strength in structures and precast concrete components. 2019.

[100] EN 12504-2 Testing concrete in structures - Part 2: Nondestructive testing Determination of rebound number. 2021.

[101] EN 12504-4 Testing concrete in structures - Part 4: Determination of ultrasonic pulse velocity. 2021.

[102] D. Breysse, J. P. Balayssac, S. Biondi, D. Corbett, A. Goncalves, M. Grantham, V. A. M. Luprano, A. Masi, A. V. Monteiro, Z. M. Sbartai, Recommendation of RILEM TC249-ISC on non destructive in situ strength assessment of concrete, Mater. Struct. 52(4) 2019 1-21. 10.1617/s11527-019-1369-2.

[103] D. Breysse, J. P. Balayssac, M. Alwash, S. Biondi, L. Chiauzzi, D. Corbett, V. Garnier, A. Gonçalves, M. Grantham, O. Gunes, S. Kenaï, V. A. M. Luprano, A. Masi, A. Moczko, H. Y. Qasrawi, X. Romão, Z. M. Sbartaï, A. V. Monteiro, E. Vasanelli, In-Situ Strength Assessment of Concrete: Detailed Guidelines. In Non-Destructive In Situ Strength Assessment of Concrete (2021)3-56, Springer, Cham. 10.1007/978-3-030-64900-5_1

[104] J. Ingham, Geomaterials under the microscope: a colour guide (2019) CRC Press.

[105] W. Mukupa, C. Hancock, G. Roberts, K. Al-Manasir, H. de Ligt, Z. Chen, Visual inspection of fire-damaged concrete based on terrestrial laser scanner data, Applied Geomatics9(3) (2017)143-158. 10.1007/s12518-017-0188-9.

[106] R. H. Courtier, The assessment of ASR-affected structures, Cem. Concr. Compos. 12(3) (1990)191-201. 10.1016/0958-9465(90)90020-X.

[107] G. S. Senesi, R. S. Harmon, R. R. Hark, Field-portable and handheld laser-induced breakdown spectroscopy: Historical review, current status and future prospects, Spectrochim. Acta, Part B, 175 (2021) 106013. 10.1016/j.sab.2020.106013.

[108] EN 196-2:2014 Method of testing cement - Part 2: Chemical analysis of cement.

[109] M.S. Shackley, X-ray fluorescence spectrometry (XRF) in geoarchaeology (2010) Springer, 10.1007/978-1-4419-6886-9.

[110] G. L. Bosco, Development and application of portable, hand-held X-ray fluorescence spectrometers, TrAC Trends in Analytical Chemistry 45 (2013)121-134. 10.1016/j.trac.2013.01.006.

[111] J. Johnson, Accurate measurements of low Z elements in sediments and archaeological ceramics using portable X-ray fluorescence (PXRF),J. Archaeol. Method Theory 21(3) (2014)563-588. 10.1007/s10816-012-9162-3.

[112] A. M. Hunt, R. J. Speakman, Portable XRF analysis of archaeological sediments and ceramics. J. Archaeol. Sci. 53 (2015) 626-638. 10.1016/j.jas.2014.11.031.

[113] EN-ISO 13196:2015 Soil quality - Screening soils for selected elements by energydispersive X-ray fluorescence spectrometry using a handheld or portable instrument.

[114] P. Mikysek, T. Trojek, N. Mészárosová, J. Adamovič, M. Slobodník, X-ray fluorescence mapping as a first-hand tool in disseminated ore assessment: sandstone-hosted U–Zr mineralization, Miner. Eng. 141(2019) 105840. 10.1016/j.mineng.2019.105840.

[115] F. F. Mendonça Filho, H. Morillas, H. Derluyn, M. Maguregui, D. Grégoire, In-situ versus laboratory characterization of historical site in marine environment using X-ray fluorescence and Raman spectroscopy, Microchem. J.147 (2019) 905-913. 10.1016/j.microc.2019.02.014.

[116] T. P. Taylor, E. Yurdakul, H. Ceylan, Concrete Pavement Mixture Design and Analysis (MDA): Application of a Portable X-Ray Fluorescence Technique to Assess Concrete Mix Proportions, 2012.

[117] A. L. Washington, W. Narrows, J. H. Christian, L. Msgwood, Quantitative analysis of concrete using portable x-ray fluorescence: Method development and validation (No. SRNL-STI-2017-00493). Savannah River Site (SRS), Aiken, SC (United States) (2017), 10.2172/1373540.

[118] Y. Zhu, D. C. Weindorf, W. Zhang, Characterizing soils using a portable X-ray fluorescence spectrometer: 1. Soil texture. Geoderma, 167(2011) 167-177.10.1016/j.geoderma.2011.08.010.

[119] B. Yokhin, X-ray fluorescence analyzer, US patent 6041095A, filled February 24, 1998 and issued March 21, 2000, https://patents.google.com/patent/US6041095A/en.

[120] J. Sherman, The theoretical derivation of fluorescent X-ray intensities from mixtures. Spectrochim. Acta 7 (1955)283-306. 10.1016/0371-1951(55)80041-0.

[121] S1 TITAN," [Online]. Available: https://www.bruker.com/en/products-and-solutions/elemental-analyzers/handheld-xrf-spectrometers/S1-TITAN.html. [Accessed 1 June 2021].

[122] "How does XRF work?," [Online]. Available: https://www.thermofisher.com/nl/en/home/industrial/spectroscopy-elemental-isotope-analysis/spectroscopy-elemental-isotope-analysis-learning-center/elemental-analysis-information/xrf-technology.html. [Accessed 1 June 2021].

[123] P. C. Kreijger, The skin of concrete composition and properties, Matériaux et Construction 17(4) (1984) 275-283. 10.1007/BF02479083.

[124] Robert F. Shannon, Jr., Compact collimating device, US patent 8,223,925 B2, filled April 15, 2010 and issued July 17, 2012, https://patents.google.com/patent/US8223925B2/en

[125] W. Kim, J. Jang, Monte Carlo simulation for the analysis of various solid samples using handheld X-ray fluorescence spectrometer and evaluation of the effect by environmental interferences. Spectrochim. Acta, Part B 180 (2021) 106203. 10.1016/j.sab.2021.106203.

[126] A. J. Nazaroff, K. M. Prufer, B. L. Drake, Assessing the applicability of portable X-ray fluorescence spectrometry for obsidian provenance research in the Maya lowlands. J. Archaeol. Sci. 37(4) (2010) 885-895. 10.1016/j.jas.2009.11.019.

[127] A. Bourke, P. S. Ross, Portable X-ray fluorescence measurements on exploration drill-cores: comparing performance on unprepared cores and powders for ‘whole-rock’analysis,Geochem.: Explor. Environ. Anal. 16(2) (2016)147-157. 10.1144/geochem2014-326.

[128] R. Cesareo, A. Castellano, G. Buccolieri, M. Marabelli, A portable apparatus for energy-dispersive X-ray fluorescence analysis of sulfur and chlorine in frescoes and stone monuments, Nucl. Instrum. Methods Phys. Res. Sect. B 155(3) (1999)326-330. 10.1016/S0168-583X(99)00256-6.

[129] M. K. Kim, J. P. P. Thedja, H. L. Chi, D. E. Lee, Automated rebar diameter classification using point cloud data based machine learning, Autom. Constr.122 (2021)103476. 10.1016/j.autcon.2020.103476.

[130] X. Li, H. Liu, F. Zhou, Z. Chen, I. Giannakis, E. Slob, Deep learning–based nondestructive evaluation of reinforcement bars using ground-penetrating radar and electromagnetic induction data. Comput.-Aided Civ. Infrastruct. Eng. (2021),https://doi.org/10.1111/mice.12798.

[131] K. Tešić, A. Baričević, M. Serdar, Non-Destructive Corrosion Inspection of Reinforced Concrete Using Ground-Penetrating Radar: A Review, Materials, 14(4) (2021) 975. 10.3390/ma14040975.

[132] D. Isailović, V. Stojanovic, M. Trapp, R. Richter, R. Hajdin, J. Döllner, Bridge damage: Detection, IFC-based semantic enrichment and visualization, Autom. Constr. 112 (2020) 103088, 10.1016/j.autcon.2020.103088.

[133] I. Bertin, R. Mesnil, J. M. Jaeger, A. Feraille, R. Le Roy, A BIM-based framework and databank for reusing load-bearing structural elements, Sustainability, 12(8) (2020)3147. 10.3390/su12083147.