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Challenges in material recycling for postwar reconstruction

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Abstract

Besides the fact that concrete recycling allows to avoid landfills disposal and contributes to a closed-cycle economy, such option may be very much in demand in war struck regions such as Ukraine, which after the end of the war, are faced with the problem of rebuilding and reconstructing. Beyond this emergency, even in peacetime extensive parts of the building stock will sooner or later need to be replaced and concrete recycling is called to play an increasing role there.

However, depending on the technology and degree to which aggregates are recycled, concrete may be characterized by poor workability, reduced mechanical properties, increased shrinkage and reduced durability. This deterioration in the properties of recycled concrete is usually attributed to the characteristics of the old cement mortar remaining on the surface of the recycled aggregates, which is best considered as an additional volume of hardened cement paste with fine aggregate and additional porosity. This article attempts to underline how such key concepts help frame the current state of knowledge about concrete recycling, understand the implications of existing regulations, in order to define pragmatic and efficient routes for broadening the use of concrete recycling in war struck regions, with specific examples regarding Ukraine.

Keywords: Concrete; Recycling; Aggregates; Porosity; Adsorption

1 Introduction

Concrete recycling has gained in importance and found its place in various norms allowing for example a certain fraction of aggregates from crushed concrete to be used. While this barely affects the CO_2 footprint of concrete that is dominated by the cement content, it however avoids landfills disposal and contributes to a circular economy.

Beyond this, we see additional needs arising in case of war struck regions, such as Ukraine. Indeed, after the end of the war, such countries face the problem of rebuilding and reconstructing vast amounts of destroyed infrastructure and residential buildings. In the case of Ukraine, so far, the damage to residential buildings based on publicly available evidence was estimated at nearly 39.4 billion U.S. dollars as of June 08, 2022. Further 30 billion U.S. dollars were recorded in direct losses from road damages. The total damage to civilian infrastructure of the war was estimated at roughly 104 billion U.S. dollars [1]. The exact numbers of destroyed houses in Ukraine are unknown and unfortunately still increasing. The estimated area of destroyed housing for three months of war may be as much as 40 million square meters of floor space [2].

If we consider that in the best pre-war years, Ukraine built up to 8 million square meters per year, it may take more than 5 years to rebuild the houses destroyed by the war. This will represent an unprecedented challenge and call for vast amounts of materials. In this context, it is worth noting that the total potential volume of old concrete in destroyed residential buildings and infrastructure can reach at approximately 20-30 million cubic meters, which, after recycling, can be effectively used as raw materials for the reconstruction of buildings and structures. This can offer important relief to the whole supply chain, removing the pressure of sourcing tremendous amounts of aggregates in a short time, but also attenuating delivery problems related to the expected to compromised state of road and rail transport.

Beyond this emergency situation, even in peacetime, material recycling has much to offer in Ukraine. According to official data from the State Statistics Service, the total area of obsolete housing stock in Ukraine is 4.33 million sq.m., according to unofficial data, about 80% of the total area of the housing stock which exceeds 1 billion sq.m. [3]. For example, in Kyiv, about 70% of precast concrete houses built in 1950-1970 (Fig. 1) are in critical condition [4]. Taking into account that, only in the 50-70s of the last century, about 400 million sq.m. of precast concrete houses were built in Ukraine, it can be expected to the total potential volume of old concrete in residential buildings that will become obsolete and needs to be replaced in the coming decades can exceed 200 million cubic meters (Fig. 2). Also, in such urban contexts, the

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*Corresponding author: V. Troian, s_troy@ukr.net opportunity of material recycling and urban mining offer benefits going beyond the limited CO_2 benefits of normal recycling.

Figure 1. Example of Ukrainian building stock of prefabricated structures produced in the 1960-1970s. Darnytska Square, Kyiv, 1966s. Source: http://starkiev.com/

Nevertheless, some words of caution are needed. Indeed, using recycled concrete for new concreting is generally characterized by a worsened workability, and the means of addressing this may have various consequences. For example:

- increasing the water content compromises strength and durability

- increasing the paste content may increase creep and cement consumption

- increasing the admixture dosage may lead to excessive delays in setting and hardening.

This central issue of the workability of recycled aggregates concrete (RAC) is mainly due to the porosity of the old cement mortar on the surface of recycled concrete aggregates [5] that absorbs water. Additionally, crushed aggregates tend to have a lower particle packing efficiency compared to natural aggregates [6].

Thus, the use of recycled aggregate is characterized by workability being more challenging to regulate. A particular aspect can be that the absorption of water over time from the old cement mortar may penalize flow retention [7]. This probably goes along with an increased consumption of admixtures, either simply because of the water sorbed by the porous aggregates, or by adsorption onto their fine surface due to the remaining hydrated cement paste. At least in part, this can be addressed by pre-wetting the recycled aggregate, which helps limiting the superplasticizer dosage.

The reduced mechanical characteristics and durability of RAC may also be due to the characteristics of the old cement mortar on the surface of the recycled aggregate. For example, it is reported that an increase in recycled aggregate content can lead to an increase in drying shrinkage [8]. For a complete substitution of large aggregates, the final mechanical strength may decrease by 10% [55, 57]. Along with the increase in recycled coarse aggregate (RCA) content, the resistance of RAC to chloride penetration and carbonation may decrease [9]. Increased capillary porosity and micro cracks in old mortar of recycled aggregates may negatively affect the frost resistance of concrete [9, 10]. Possible ways to keep this under control include addition of air entraining agents, reducing the W/C ratio and pre-wetting (internal curing) of recycled aggregates [10, 11, 12]. The use of internal curing can also increase the crack resistance and dynamic modulus of elasticity of RAC [12].

The old cement mortar actually represents an additional volume of hardened cement paste with fine aggregate (Fig. 3). This may further increase the shrinkage, creep and permeability of the RAC and reduces its strength and modulus of elasticity [9].

Figure 2. Schematic illustration of the postwar reconstruction challenge Ukraine will face, resulting from a combined effect of severe ageing of structures from the USSR time and destruction due to the war, leading to a huge demand for concrete reconstruction. At the same time, the abundance of mineral demolition waste offers opportunities for recycled aggregate concrete (RAC) to play a major role in filling the demand for concrete in the coming years.

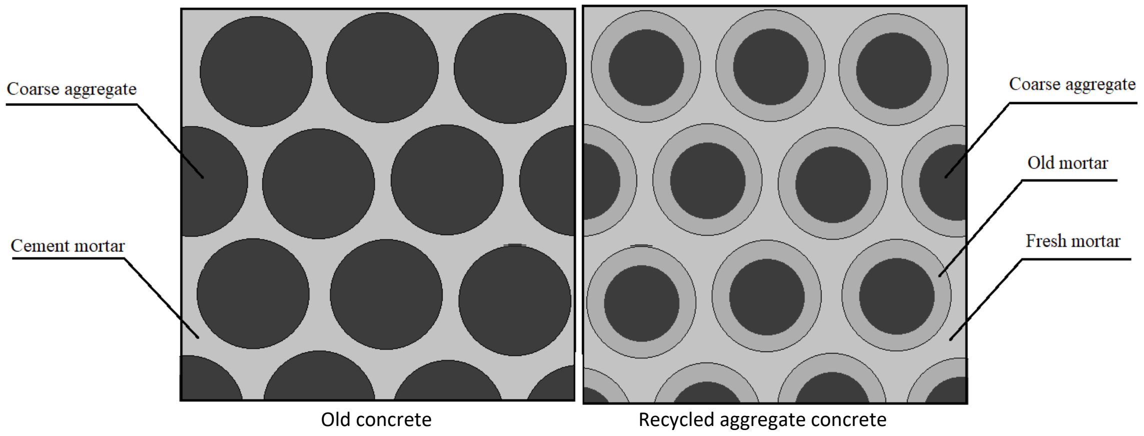

Figure 3. Recycled aggregate concrete structure model.

These aspects provide a rationale for the current "rule of thumb" that the amount of recycled aggregates should be limited to minimize the negative effects [9], with a current limit being about 30-50% replacement of the coarse aggregate (See Table 1).

The present paper reviews such questions, with a focus on contextualizing contemporary knowledge on concrete recycling with respect to postwar reconstruction in Ukraine. It underlines specificities, and concerns that this may arise if such recycling is to be carried at the scale needed by the devastating ongoing war. Before this however, it is worth taking a quick look at the state of present norms, since beyond the emergency, these will dictate the range of possibilities.

2 Recycling in the norms

Ukraine uses European norms and to date in Ukraine EN 206:2013 + A1:2016, states that the use of coarse recycled aggregate in the concrete can increase both drying shrinkage and creep, while decreasing the modulus of elasticity. It should be noted that this standard provides recommendations only for the use of coarse recycled aggregates with d > 4 mm.

To keep the negative effects under control, EN 206:2013 + A1:2016 sets limits to the percentage of coarse aggregate replacement (Table. 1). According to this, two classes of aggregates, noted A and B, are defined. The classification is based on the nature and amounts of the recycled materials, specified in Table 2 according to European standard EN 12620. For example, type A aggregates should include at least 90% (Rc_{90}) recycled concrete and mortar, or at least 95% (Rcu_{95}) recycled concrete, mortar, aggregate and natural stone. For the remaining part, aggregate of type A may not contain more than 10% (Rb_{10-}) clay and calcium silicate masonry units, aerated (non-floating) concrete, no more than 1% (Ra_{1-}) bituminous materials, no more than 2% (FL_{2-}) floating material in volume and no more than 1% (XRg_{1-}) clay and soil, metals, non-floating wood, plastic and rubber, gypsum plaster, glass.

For recycled aggregate type A & B the percentage of coarse aggregate replacement must not exceed 50% by mass for exposure class X0. For recycled aggregate type A, the replacement level must not exceed 30% for exposure classes XC1-XC4, XF1, XA1 and XD1. For the remaining exposure classes, may be used up to 30% replacement levels if the aggregates come from a known source with the same exposure class as the new concrete will be exposed to.

For type B and apart X0 exposure, the situation is much more restrictive because of the greater range of allowed compositions. For example, the maximum percentage of replacement must not exceed 20% for exposure classes XC1-XC2 and is not allowed for all other exposure classes. Further to this aggregates of type B may not be used for compressive strength classes above C30/37.

Thus, type A recycled aggregates may offer the widest options for extensive reconstruction in a war struck country. However, it is important to be aware that recycled building materials may be contaminated with sulphates in the case of civil buildings (gypsum plaster on walls, plasterboard, etc.) and chlorides in the case of infrastructure (chlorides accumulated because of de-icing agents, seawater exposure, or use of calcium chloride as hydration accelerator). Thus, there is a risk for the new concrete to have an increased sulphate and/or chloride content, which raises concerns about sulfate attack and damage to steel reinforcement, respectively. Accordingly, criteria and limits are given in the European standards (EN 206:2013+ A1:2016, EN 12620). Although the existing standards define the methods and frequency of control, use rapid and simple tests to identify sulfate or chloride rich recycled aggregates, ideally for screening purposes on-site, deserve further development.

Table 1. Recommendation for maximum percentage of replacement of coarse aggregates (% by mass) according to European standard EN 206:2013+ A1:2016. The compositions abbreviations are defined in Table 2. The subscript numbers indicate the maximum amount if followed by a minus sign. Otherwise, the subscript numbers indicate one of the minimum amounts to choose from (*Rc* or *Rcu*).

Recycled aggregate type	**Exposure classes**			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All other exposure classes [a]
Type A: (Rc_{90}, Rc_{u95}, Rb_{10}-, R_{a1}-, *FL2*-, *XRg1*$_{-}$)	50 %	30%	30%	0%
Type B [b]: (Rc_{50}, Rcu_{70}, Rb_{30}-, Ra_{5}-, FL_{2}-, XRg_{2-})	50 %	20%	0%	0%

[a] Type A recycled aggregates from a known source may be used in exposure classes for which the original concrete was designed with a maximum percentage of replacement of 30 %.

[b] Type B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.

Table 2. Categories for constituents of coarse recycled aggregates (according to European standard EN 12620).

Constituent	**Description**
Rc	Concrete, concrete products, mortar. Concrete masonry units
Ru	Unbound aggregate, natural stone. Hydraulically bound aggregate
Rb	Clay masonry units (i.e. bricks and tiles). Calcium silicate masonry units. Aerated non-floating concrete
Ra	Bituminous materials
FL	Floating material in volume
X	Other: Cohesive (i.e. clay and soil). Miscellaneous: metals (ferrous and non-ferrous), non-floating wood, plastic and rubber. Gypsum plaster
Rg	Glass

3 Recycling technology

Recycling technology has a significant impact on the characteristics of recycled aggregate and, consequently, concrete. Various methods of recycling aggregates are known, which may include the removal of cement mortar from the surface of the aggregate.

The most convenient and easy to implement is a mechanical method of recycling aggregates [13]. This basically consists in crushing old concrete and sieving it to keep aggregates above a critical size. While offering a high throughput, this also leads to large amounts of paste remaining adhered to the recycled aggregates. This has several disadvantages, which include a negative impact on the workability of the concrete mix and reduced compressive strength of RAC [6, 9].

Another approach is to subject the concrete to be crushed to a heat treatment that dehydrates the old cement paste, which facilitates its removal from the surface of recycled aggregates during crushing [13, 51, 52]. On the downside, this method is high energy demanding. This can however be partially compensated by the reuse of the recovered binder dehydrated at moderate temperatures, such as about 450 °C [23]. The choice of this temperature is guided by the fact that it allows the dehydration of C-S-H, portlandite decomposition to the calcium oxide and decomposition of ettringite (occur at temperatures around 100 °C) [30]. When ground (enough), the recovered paste heated to 450 °C has been reported to lead to a similar compressive strength as OPC, but with a poor workability [23]. In any case, it is worth noting that the use of recycled binders (obtained from grinding and heating) may replace part of the cement in concrete production, with some limitations in the use and the need to solve the problem of workability. In practice however, the recycled powder will not purely come from the cement paste, but probably also include fillers and/or crushed sand, which would reduce the binder efficiency.

A further proposed method is to pre-soak the recycled aggregates in acid to destroy cement hydration products and remove the old mortar from the surface of recycled aggregates [14]. Aggregates are then rinsed and sieved before use. However, this method significantly increases the cost of concrete production and contaminates recycled aggregates with the conjugate base of the acid as for example chlorides, sulfates, and other undesirable compounds, depending on the type of acid used. To the best of our knowledge, this approach has not yet been followed-up in practice.

Yet another approach to remove paste from RCA uses microwaves to create thermal stresses at the interface between the old cement mortar and the aggregate, making it easier to recover clean aggregates during crushing. This method is less energy-intensive than conventional heating and machine grinding [15] but it raises certain safety concerns about the industrial scale use of microwaves. A similar approach uses ultrasounds instead of microwaves to clean recycled aggregates [16].

While the previous methods all aim at making it easier to remove the cement paste while producing the recycled aggregates, another approach aims at modifying the paste to make its presence less detrimental. This involves an accelerated carbonation that increases the paste density and reduces the porosity, at least for OPC systems, thereby reducing the water absorption and porosity of recycled aggregates [17]. This method provides a double environmental benefit by recycling concrete and capturing carbon dioxide. For this reason, it is capturing a lot of interest and presents strong development potential. However, it should be noted that the carbonation rate and therefore the potential CO_2 uptake of coarse aggregates can be much lower than that of fine aggregates [59-61]. In addition, generally highly concentrated carbon dioxide gas is required, which may not always be available.

Considering the challenges in obtaining high quality recycled aggregates, it has been proposed to more extensively grind all concrete waste to obtain fine rather than coarse aggregates [18]. Fine aggregate recycled in this way can replace 100% of the sand in concrete, however, this worsens the workability of the concrete mix and increases the consumption of the superplasticizer [5]. Besides, unlike recycled coarse aggregate, whose use is regulated by EN 206:2013 + A1:2016, there are no recommendations for the use of fine recycled aggregate in this standard.

Regardless of the approach, but more particularly for processes leaving high amounts of highly sorptive old cement paste, pre-wetting is an effective way of mitigating negative impacts of recycled aggregates on rheology. It is also easy to implement, even if in terms of logistics it calls for an additional step and possible reduced productivity. It is also reported that this pre-wetting may mitigate problems of drying shrinkage and associated cracking [9].

4 Hardened paste volume

A critical aspect with recycled aggregates is the porosity of the recycled paste that remains adhered to the original aggregates. The previous section overviewed various processes to reduce its amount and/or change its properties. However, since the cheapest route for production of recycled aggregates does not address this issue, we must also assume that Ukraine reconstruction will deal with minimum processing of recycled aggregates, leading to rather large paste contents. This section therefore proposes a conceptual overview on the role of the hardened paste volume remaining adhered to recycled aggregates.

Let us consider the standards (in terms of design compressive strength of concrete) by which panel houses were built in Ukraine during the USSR time. GOST 12504-67 «Concrete and reinforced concrete panels for internal walls in large-panel buildings» and GOST 9561 - 66 «Reinforced concrete multi-hollow panels for floors in buildings» regulate design strength of concrete of at least 20 MPa. GOST 9818-67 «Reinforced concrete flights of steps and stair landings for residential and civil buildings» regulate design strength of concrete between 20 and 30 MPa. GOST 11118-65 «Autoclave cellular concrete panels for exterior walls of residential and public buildings» and GOST 11024-72 «Lightweight concrete panels for external walls of house and civil buildings» provide design strengths of concrete from 3 to 10 MPa. However, such lightweight concrete products should be excluded from the recycling cycle for obtaining type A aggregates (by the criteria of the content of aerated non-floating concrete and floating material in volume, Tables 1 and 2). Thus, for type A aggregates we expect RCA to have a design strength at least 20 to 30 MPa.

Further to this, we can estimate typical paste volumes of those concrete from norms SN 386-68 «Typical norms of cement consumption in concrete of precast concrete and reinforced concrete mass production» for the above products with design strength of concrete of 20 MPa (release strength of concrete at least 70% of design) in heat treatment conditions, depending on the workability of the concrete mix, most probably use of CEM II/A-S 32.5, CEM II/B-S 32.5 or CEM III 32.5 with a content of about 240-325 kg/m^3 at W/C ~ 0.7.

Depending on the workability of such concrete, the volume of coarse aggregate (fractions of 5-10 mm and 10-20 mm, or 5-20 mm) is expected to be 40-50%. Respectively, the volume of old mortar from cement paste with fine aggregate (often fractions smaller than 1 mm) is 50-60%, with the cement paste itself being about 24-33 %. Some of this cured cement mortar remains on the surface of the recycled aggregate after recycling and can impact various properties of RAC, but this will depend on recycling technology and the paste strength, since weaker cement paste is easier to separate from the aggregate.

The compressive strength, for example, is mostly dictated by the W/C ratio of the paste. So, if the W/C of the RCA paste is lower than the W/C of new concrete, we would not expect too much adverse impact on strength from the old paste, unless it gets damaged during the grinding. With most RCA expected to come from concrete with 20 MPa design strength, this means we would best use such aggregates for the production of new concrete not exceeding a similar strength requirement. Considering that postwar reconstruction will to a large extent concern the reconstruction of housing with generally moderate strength requirements, we consider it feasible to use RCA from demolition concrete of buildings in Ukraine dating back to the USSR time. Nevertheless, it should be considered that the actual strength of the original concrete may differ from its design strength (both upward and downward) due to more complete hydration, carbonation or chemical attack. Therefore, rapid compressive strength test methods for on-site use would be beneficial for screening demolition materials with respect to their applicability as RCA.

When designing the durability of RAC, the right decisions may not be so obvious. Indeed, the durability of RAC will depend not only on the W/C of new and old concrete, but also on the chemical composition of the cements used in them and products of their hydration and corrosion. Thus, the guideline of using aggregates of known origin in similar exposure conditions appears a reasonable way forward

5 Rheological properties of recycled concrete

The negative impact of recycled concrete aggregate on rheology has two origins: the angularity of the aggregates and the porosity of the paste [6]. Schematically, the effect of angularity should be constant over time. Thus, while it makes it more challenging to reach the initial workability, flow retention should then be less challenging to achieve. Ways to deal with angularity effect on rheology would include adding more water (to be avoided), increasing the paste volume (negative for concrete composition) or increasing the admixture dosage (possibly increasing setting time). Most of these effects may indirectly lead to producing concrete of with more flow retention problems, but as mentioned above we a priori rank this as a secondary factor.

Of greater concern is the role of the residual hardened cement paste present on the recycled aggregates and its tendency to absorb water over time. Indeed, it is generally reported that the initial workability of concrete mixes containing RCA is usually satisfactory [19, 20, 21], but tends to worsen rapidly thereafter [7]. Not too surprisingly, this loss of workability depends on the percentage of RCA in the concrete mix, thus laying the grounds for putting a cap on the amount of recycled aggregates in the norms. This at least prevents unwanted (and worse undeclared) water additions prior to placing the concrete.

To get a sense of the significance of the water absorption, we return to our estimate that RCA may have a content of old mortar between 0 and 60% with a porosity of 20% (estimated assuming full hydration and that the volume of hydrates is double that of the initial anhydrous cement). We consider exposure class X0 for which the RCA replaces up to 50% of normal coarse aggregate. In this case, for an average old mortar content of 30% in the RCA, one would then have an additional porosity of about 1.46% (fig.4). If this porosity gets filled with water, for a W/C 0.70 concrete, it represents a water loss could be about 7.4 %, which is very substantial.

Consequences on rheology are delicate to assess a priori. However, we may assume that the concrete yield stress changes proportionally to the change in the paste yield stress, which, in turn, is conditioned by its water loss. The paste yield stress change can be estimated from [22] and is found to increase by a factor 1.7 for the above example. To qualify what this represents in terms of slump loss, we use the expression proposed by Roussel et al relating yield stress to slump [42]. Considering a plasticized ready-mix concrete with 24, 18 and 12 cm initial slump, the appropriate yield stress change factor (1.7 in the previous example), we obtain an expected decrease of slump to 23, 12 and 2 cm respectively with the old mortar content in RCA of 30% or to 23.5, 16 and 8 cm respectively with the old mortar content in RCA of 15% at as shown in Fig.4. The same figure shows the corresponding lost water change depending on the amount of RCA and old mortar remaining on the RCA.

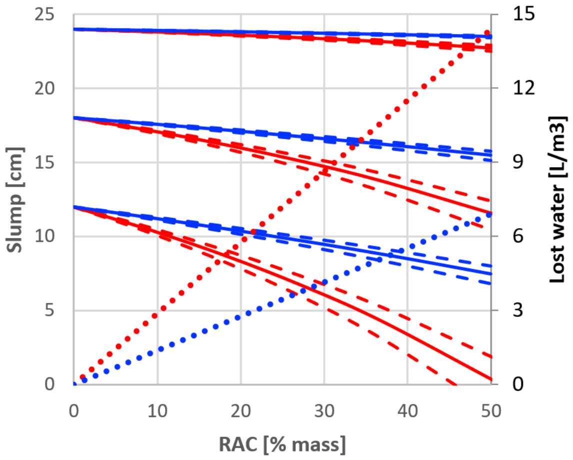

Figure 4. Slump and water absorption in relation to RCA content. Water absorption (secondary axis, diagonal rising dotted lines) assumes the old concrete had a W/C of about 0.70. Two cases of old mortar contents in the RCA are shown: 15% (blue) and 30 % (red). Three different initial slump values are considered (12, 18, 24 cm). The estimated consequence from water absorption in RCA is reflected by the slump decrease from those values. For each case, three different W/C values of the new concrete are considered: 0.5 (low discontinuous line), 0.6 (continuous line) and 0.7 (upper discontinuous line).

The effective water loss due to the absorption by the recycled aggregates could be compensated in the mix-design. However, current RCA water absorption measurement have been shown to be difficult at least in the case of measurement of sand-type fine porous aggregates [53]. Moreover, as for any hardened concrete testing, the typically used drying protocol at 105°C was shown to dehydrate some of the sulfo-aluminates [54, 55, 56] and affect porosity and measured water absorption. It was concluded that water intake by RCA is often over-estimated. As a consequence, overcompensation of absorbed water usually leads to a higher effective W/C than expected, with negative consequences for strength, shrinkage and durability.

Moreover, the absorption of water by the recycled aggregates is not instantaneous. The kinetics of absorption strongly depends on the porosity and porosity size distribution of the recycled concrete. From a daily practice point of view, very fast absorption rates (on time scales of a couple minutes) are not an issue, as the aggregates shall absorb the excess water during mixing. Very long absorption kinetics are not an issue either for workability retention as setting shall occur before any meaningful absorption of the RCA. In such a situation, absorption does not need to be covered, and water content in the fresh mortar is expected to stay constant before casting. However, in practice, most studies have shown that the absorption kinetics characteristic time are in an intermediate range from some tens of minutes to a couple hours [55, 58]. Thus, water compensation and control of workability are challenging.

The loss of workability has many fold implications for RCA concrete. First it reduces the time available for placing and may narrow its use to precast only. Second it limits the amount of recycled aggregates. Therefore, providing well-defined protocols and quality controls measures appear an essential way of guaranteeing high quality RAC. Importantly also, this would provide a performance base means of expanding provisions in the current norms.

Pre-wetting RCA has a positive effect on both the initial workability of the concrete mix and its retention, but its industrial implementation can be challenging [7]. It is however worth the effort because the proper regulation of water content and the use of a two-stage mixing allow the replacement of up to 100% of the coarse aggregate RCA while ensuring the required initial flowability of the concrete mixture [24]. So, such options should be seriously considered for the postwar reconstruction.

Further to this, chemical admixtures offer an important lever to control concrete rheology. In particular, depending on their molecular structure polycarboxylate-type superplasticizers can increase their dispersing effect over time [25]. This and other structure function modifications may provide means of compensating the loss of fluidity over time in RCA. It is however not obvious how general such solutions may be because we face two independent kinetic processes of completely different nature and the objective is to have them compensate each other in term of their macroscopic consequences. On the one hand, we have water sorption into the hardened cement paste, which is governed by sorptivity of porosity of the old paste, as well as its exposed surface. On the other hand, we have a chemical modification of PCEs, that would mainly dependent on pH and therefore both on the alkali content of the fresh cement and on the water to cement ratio. Pragmatic admixture formulation guidelines would appear as an important way of dealing with such issues on a short term.

6 Shrinkage

Increased shrinkage of recycled concrete leads to increased crack formation and decreased durability. A distinction is made between autogenous shrinkage due to chemical reactions between cement and water, drying shrinkage due to evaporation of free water from the pores of hardened concrete and plastic shrinkage that takes place before final setting [26, 27]. Autogenous shrinkage results from self-desiccation produced by cement hydration and has consequences for low W/C concrete since it has no more enough water for hydration. For RAC, this definition may deserve some reconsideration for low W/C and not pre-wetted RCA as their sorption may compete for water with hydration reactions. However, overall, autogenous shrinkage is not expected to be a major problem. Compared with normal concrete, RAC with pre-wetted RCA has a lower autogenous shrinkage because of the internal curing effect [26].

With a content more than 50% RCA plastic shrinkage may however be more significant. Indeed, water absorbed by the RCA leads to a volume reduction of the paste. Such volume change taking place after placing, and in particular after initial setting will lead to plastic shrinkage and possible related cracking. In this regard, it has been reported based on ring test results that for self-compacting concrete (Fig.5), plastic shrinkage cracking begins when more than 2 l/m^2 of mixing water evaporates [45]. Considering the concrete thickness in the ring test, we infer that this water loss is roughly equivalent 25 L/m^3. From Figure 4, we see that about 15 L/m^3 could be absorbed in concrete with a 50% replacement of coarse aggregates with aggregates having a 30% vole of old mortar. While this alone would not cause critical plastic shrinkage, it nevertheless makes the *concrete a priori* much more susceptible to it.

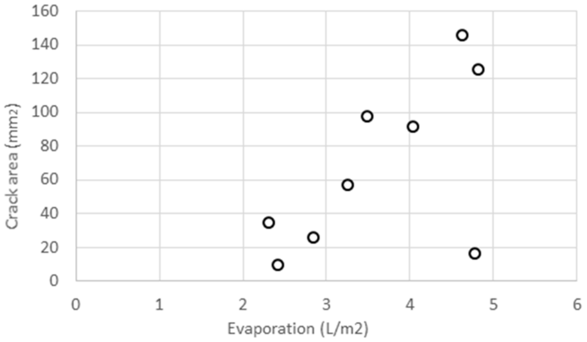

Figure 5. Plastic shrinkage cracking severity versus the evaporation of mixing water according to results the ring test method

Drying shrinkage is more complex to assess, because of the unclear contribution of the old mortar in this process [26]. As hydration progresses and due to drying shrinkage, the pore refinement of the hydrating paste will tend to draw back water from the capillary pores of the old paste on the RCAs, which may cause shrinkage of the old mortar. While old mortar will be more rigid and less prone to shrinkage than new mortar, its potentially greater porosity can be a significant negative factor. In any case, different shrinkage behavior between the old and new mortar may introduce cracks at the interfaces of RCA and new mortar.

Globally however, it can be said that to reduce risks from plastic or drying shrinkage, it is recommended to provide appropriate care for concrete and to use a combination of mineral, chemical expanding and shrinkage reducing admixtures [28, 29]. Further to this, a known method of reducing drying shrinkage is to reduce the pore space of concrete by reducing the paste volume and/or the water-cement ratio, both of which would require superplasticizers to maintain sufficient workability [31]. The reduction of the drying shrinkage of concrete when using superplasticizers can be increased by using fillers such as microsilica, fly ash and limestone [32, 33]. The introduction of metakaolin when using recycled aggregates with a high content of gypsum (in fine form) enhances ettringite formation and may provide compensation for shrinkage deformations of concrete [33]. However, the content of fillers can also increase the paste volume (more water needed), which can increase all forms of shrinkage [26, 34].

Another approach is Internal Curing. It can be achieved either with organic superadsorbant polymers or pre-wetted lightweight aggregates, but recycled aggregates have also been claimed to be effective [35, 36, 37].

In all cases, to be effective, it is necessary to provide water for saturating either of these, which in the case of RCA brings us back to the need of pre-wetting, even if this is adds some complications in practice.

7 Durability

In the context of postwar reconstruction, a large portion of the concrete demand will be for housing. Residential buildings are generally not severely exposed to chlorides, and the dominant exposure classes are those related to carbonation (Table 3).

To ensure the durability of concrete in exposure classes XC1-XC4, according to EN 206, the W/C - ratio should be in the range 0.50 to 0.65 and minimum strength classes C20/25 to C30/37 should be achieved. With respect to the properties expected for demolition waste originating from concrete made in Ukraine during USSR times (compare section 4), special precautions in producing RAC may thus be needed to satisfy these requirements. The type of precautions will depend significantly on the recycling technology used. For instance, if RCA with substantial fractions of old mortar adhering to the aggregates are used, again rapid tests for strength screening of the recycled materials are important.

The deemed-to-satisfy approach described in Table 3 aims at minimizing the risk of corrosion of reinforcing steel embedded in concrete during the design service life of a structure (typically 50 y). In this regard, cyclic wetting and drying conditions (XC4) are considered the most severe, as the dry stages permit carbonation of the concrete, while the wet stages can lead to substantial corrosion rates once the carbonation front reaches the reinforcing steel. For the performance of RAC, it is thus crucial to examine the behavior in these two different conditions.

The resistance to carbonation will depend on factors such as cement type, porosity and permeability of the concrete. A very important, but often overlooked aspect of concrete technology, is that carbonation (and chloride penetration) is not much affected by the paste volume, provided the water to cement ratio is kept constant [43]. For example, the carbonation depth is virtually independent of the volume of aggregates. For RAC, however, literature studies reported a tendency for higher carbonation depths when larger fractions of RCA are used [38, 46]. Further influences are related to the size and shape of the RCAs and the amount and properties of adhered paste, which are critically influenced by the technology used for recycling (section 3). This dependency on actual recycling technology makes it difficult to define generally valid statements on the resistance to carbonation of RAC.

With this in mind, we examine the question of durability of recycled concrete. Most importantly, the central question is to know the water cement ratio used and reaction capacity of concrete towards CO_2 (or chlorides). As alluded to above, the residual reaction capacity of the original concrete with respect to CO_2 and chlorides would be worth considering. The reaction capacity with respect to CO_2 may be determined from a chemical analysis of the amount of bound CO_2 in concrete after carbonation tests, or approximately calculated from the amount of cement and the degree of its potential carbonation [44].

However, even if concrete carbonates, it does not necessarily mean that steel corrosion occurs at significantly high rates and that durability of the structure becomes problematic. Recent studies [47, 48] have revealed the important role of moisture at the steel-concrete interface in controlling the rate of corrosion. Additionally, the microstructure (pore structure) of the cementitious matrix surrounding the steel is an important factor [49]. Therefore, for the performance of RAC in XC exposure conditions, the following properties are considered the most relevant:

- Moisture transport and retention of RAC: It should be avoided that significant amounts of liquid water reach the embedded reinforcing steel during the life of the structure. This may be achieved either by ensuring sufficiently high cover depths or by controlling the moisture transport properties of RAC. Nevertheless, since such design approaches are not even established for normal concrete, further research is needed in order to devise design rules that may be employed in practice.
- Pore structure at the steel-concrete interface. It is expected that upon concrete casting, the reinforcing steel is primarily surrounded by a matrix of cement paste, and that aggregates (both natural and RCAs) will generally not be in immediate contact with the steel [50]. Nevertheless, the presence of RCAs may influence the steel-concrete interfacial zone due to processes discussed earlier in this paper, such as sorption of mixing water, shrinkage cracking, etc.

Clearly further research is needed to clarify these aspects and their influence on the corrosion rate. Means of reducing porosity and increasing the resistance of RACs to chloride and water penetration as well as carbonation may be introducing mineral additives such as microsilica [39], metakaolin [40] and fly ash [41], which should not lead to an increase in W/C. Furthermore, concrete surface treatments may offer additional routes of ensuring durability, especially if the available demolition waste's properties are not adequate to fully satisfy the durability criteria by means of concrete mix proportioning.

In view of the above it appears once again that any means of removing the old cement paste from recycled aggregates, altering their sorption capacity or pre-saturating them would benefit RAC. Simple performance-based guidelines would therefore be very beneficial in raising the impact of such methods.

Table 3. Exposure classes and requirements for carbonation according to European standard EN206.

Exposure class	Description	Examples	Max. W/C	Min. strength class	Min. cement content
XC1	Dry or permanently wet	Indoor with low air RH or permanently submerged	0.65	C20/25	260 kg/m3
XC2	Wet, rarely dry	Long-term water contact (e.g. underground structural members)	0.60	C25/30	280 kg/m3
XC3	Moderate humidity	Indoor with moderate or high air RH, external concrete sheltered from rain	0.55	C30/37	280 kg/m3
XC4	Cyclic wet and dry	Periodic contact to water (e.g. facades, balconies)	0.5	C30/37	300 kg/m3

8 Conclusions

Most sources state that porosity, adsorption, mechanical and chemical properties of the old mortar remaining on the recycled aggregates can have a negative impact on the rheological properties of the new concrete, reduce its strength, modulus of elasticity, frost resistance, and resistance to chloride penetration and carbonation, while increasing shrinkage and creep. Various approaches are feasible to minimize such negative effects, including reducing the content of old mortar on the surface of recycled aggregate, reducing its porosity and water adsorption properties, sorting, limiting the content and controlling the size of such aggregates in recycled concrete, or pre-saturating the recycled aggregates.

Recommendations of EN 206:2013 + A1:2016 for recycled aggregate are summarized in Tables 1 and 2. A key take away is that the highest replacement level is 50% for exposition class, which we took as boundary to discuss possible consequences of RCA on concrete properties. For this we specifically considered the old concrete most abundant in Ukraine and estimated the average porosity of its hardened mortar. This together with the range of concrete most needed to be produced led us to defining possible values of slump loss that could be expected. This underlines the importance of pre-saturating the old mortar on RCA. We see this as the most viable option if large amounts of RCA are to be used in postwar reconstruction. Indeed, other technologies do not appear advanced enough for a rapid roll-out at the scale that would be needed in Ukraine. The pre-saturation could best be achieved by two-stage mixing and could probably find its way in regular practice in a constrained market.

In terms of shrinkage, the greatest issues are expected to be in terms of plastic shrinkage, whereby water is removed from the paste by suction into the old mortar. The situations for drying shrinkage and autogeneous shrinkage are more delicate to assess. In any case, a pre-saturation o the RCA is recommended as it would attenuate the consequences of any of these three shrinkage types. This may of course be complemented by using an appropriate combination of mineral expansive agents and shrinkage reducing admixtures.

It is reported that recycled concretes have worse resistance to carbonation and chloride and water penetration. Reasons for this are not trivial and depend significantly on the recycling technology. In the context of postwar reconstruction, a large portion of the concrete demand will be for housing, and the dominant exposure classes are those related to carbonation. Corrosion resistant buildings can be achieved by controlling the carbonation resistance of the recycled concrete, its cover depth, as well as the moisture transport properties to limit corrosion rates during wet periods in XC4 exposures. Furthermore, concrete surface treatments may offer additional routes for ensuring durability, especially if the available demolition waste's properties are not adequate to fully satisfy the durability criteria by means of concrete mix proportioning.

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References

[1] https://www.statista.com/statistics/1303344/ukraine-infrastructure-war-damage/ Accessed December 2022.

[2] https://www.nzz.ch/meinung/ukraine-konferenz-in-lugano-es-geht-um-freiheit-nicht-um-die-schweiz-ld.1692007 Accessed December 2022

[3] https://24tv.ua/ru/starye-doma-vechnaja-diskussija-dozhdutsja-gorjachie-novosti_n1731273 Accessed December 2022

[4] https://thepage.ua/real-estate/snos-hrushevok-v-kieve-kogda-startuet-i-chto-izvestno-o-proekte Accessed December 2022

[5] C. Bu, L. Liu, X. Lu, D. Zhu, Y. Sun, L. Yu, Y. OuYang, X. Cao, Q. Wei, The Durability of Recycled Fine Aggregate Concrete: A Review. Materials. 2022; 15(3): 1110. https://doi.org/10.3390/ma15031110

[6] F. de Andrade Salgado, F. de Andrade Silva, Recycled aggregates from construction and demolition waste towards an application on structural concrete: A review, Journal of Building Engineering, Volume 52, 2022. https://doi.org/10.1016/j.jobe.2022.104452

[7] I. González-Taboada, B. González-Fonteboa, J. Eiras-López, G. Rojo-López, Tools for the study of self-compacting recycled concrete fresh behaviour: Workability and rheology. J. Clean. Prod. (2017) 156: 1-18. https://doi.org/10.1016/j.jclepro.2017.04.045

[8] F.A. Soomro, B.A. Memon, M. Oad, A.H. Buller, Z.A. Tunio, Shrinkage of Concrete Panels Made with Recyclable Concrete Aggregates. Engineering, Technology & Applied Science Research, (2019) 9(2): 4027-4029. https://doi.org/10.5281/zenodo.2648005

[9] B. González-Fonteboa, S. Seara-Paz, J. de Brito, I. González-Taboada, F. Martínez-Abella, R. Vasco-Silva, Recycled concrete with coarse recycled aggregate. An overview and analysis. Materiales De Construcción, (2018) 68(330): e151. https://doi.org/10.3989/mc.2018.13317

[10] H. Guo, C. Shi, X. Guan, J. Zhu, Y. Ding, T.C. Ling, H. Zhang, Y. Wang, Durability of recycled aggregate concrete - A review, Cement and Concrete Composites (2018) 89, 251-259. https://doi.org/10.1016/j.cemconcomp.2018.03.008

[11] S.T. Yildirim, C. Meyer, S. Herfellner, S. Effects of internal curing on the strength, drying shrinkage and freeze-thaw resistance of concrete containing recycled concrete aggregates. Constr. Build. Mater. (2015) 91: 288-296. https://doi.org/10.1016/j.conbuildmat.2015.05.045

[12] M. El-Hawary, A. Al-Sulily, Internal curing of recycled aggregates concrete. J. Clean. Prod. (2020) 275: 122911. https://doi.org/10.1016/j.jclepro.2020.122911

[13] K. Pandurangan, A. Dayanithy, S.O. Prakash, Influence of treatment methods on the bond strength of recycled aggregate concrete. Constr. Build. Mater. (2016) 120: 212-221. https://doi.org/10.1016/j.conbuildmat.2016.05.093

[14] S. Ismail, M. Ramli, Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. Constr. Build.Mater. (2013) 44: 464-476. https://doi.org/10.1016/j.conbuildmat.2013.03.014

[15] A. Akbarnezhad, K.C.G. Ong, M.H. Zhang, C.T. Tam, T.W.J. Foo, Microwave-assisted beneficiation of recycled concrete aggregates. Constr. Build. Mater. (2011) 25: 3469-3479. https://doi.org/10.1016/j.conbuildmat.2011.03.038

[16] A. Katz, Treatments for the improvement of recycled aggregate. J. Mater. Civ. Eng. (2004) 16: 597-603. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:6(597)

[17] Z. Zhao, S. Remond, D. Damidot, L. Courard, F. Michel, Improving the properties of recycled concrete aggregates by accelerated carbonation. Proceedings of the Institution of Civil Engineers - Construction Materials (2018) 171: 126-132. https://doi.org/10.1680/jcoma.17.00015

[18] Z. Yang, S. Liang, H. Mo, Y.W. Chen, Treatment and Recycling Method of Construction Waste. CN101099974, 9 January 2008. https://patentscope.wipo.int/search/es/detail.jsf?docId=CN83294353

[19] V. Revilla-Cuesta, M. Skaf, A. Santamaría, J.J. Hernández-Bagaces, V. Ortega-López, Temporal flowability evolution of slag-based self-compacting concrete with recycled concrete aggregate, Journal of Cleaner Production, (2021) 299. https://doi.org/10.1016/j.jclepro.2021.126890

[20] M. Safiuddin, U.J. Alengaram, M.M. Rahman, M.A. Salam, M.Z. Jumaat, Use of recycled concrete aggregate in concrete: a review. Journal of Civil Engineering and Management (2013) 19(6): 796-810. https://doi.org/10.3846/13923730.2013.799093

[21] T.-Y. Tu, Y.-Y. Chen, C.-L. Hwang,Properties of HPC with recycled aggregates, Cement and Concrete Research (2006) 36(5): 943–950. https://doi.org/10.1016/j.cemconres.2005.11.022

[22] A. Mantellato, R.J. Flatt, Shifting factor-A new paradigm for studying the rheology of cementitious suspensions. J Am Ceram Soc. (2020) 103: 3562- 3574. https://doi.org/10.1111/jace.17040

[23] J. Wang, M. Mu, Y. Liu, Recycled cement. Construction and Building Materials (2018) 190: 1124-1132. https://doi.org/10.1016/j.conbuildmat.2018.09.181

[24] E. Güneyisi, M. Gesoğlu, Z. Algın, H. Yazıcı, Effect of surface treatment methods on the properties of self-compacting concrete with recycled aggregates. Constr. Build. Mater. (2014) 64: 172-183. https://doi.org/10.1016/j.conbuildmat.2014.04.090

[25] G. Gelardi, S. Mantellato, D. Marchon, M. Palacios, A.B. Eberhardt, R.J. Flatt, 9 - Chemistry of chemical admixtures, Editor(s): Pierre-Claude Aïtcin, Robert J Flatt, Science and Technology of Concrete Admixtures, Woodhead Publishing (2016) 149-218. https://doi.org/10.1016/B978-0-08-100693-1.00009-6

[26] Y. Mao, J. Liu, C. Shi, Autogenous shrinkage and drying shrinkage of recycled aggregate concrete: A review, Journal of Cleaner Production, (2021) 295. https://doi.org/10.1016/j.jclepro.2021.126435

[27] A. Leemann, P. Nygaard, P. Lura, Impact of admixtures on the plastic shrinkage cracking of self-compacting concrete. Cement and Concrete Composites (2014) 46: 1-7. https://doi.org/10.1016/j.cemconcomp.2013.11.002

[28] J. Weiss, N. Berke, Shrinkage reducing admixtures in early age cracking in cementitious systems. Report of RILEM Technical Committee 181-EAS. Early ageshrinkage induced stresses and cracking in cementitious systems. RILEM Publications SARL (2002) 350.

[29] M. Collepardi, A. Borsoi, S. Collepardi, J.J. Ogoumah Olagot, R. Troli, Effects of shrinkage reducing admixture in shrinkage compensating concrete under non-wet curing conditions. Cement and Concrete Composites (2005) 27 (6): 704-708. https://doi.org/10.1016/j.cemconcomp.2004.09.020

[30] A. Soultana, M. Galetakis, A. Vasiliou, K. Komnitsas, D. Vamvuka, Utilization of Upgraded Recycled Concrete Aggregates and Recycled Concrete Fines in Cement Mortars. Recent Progress in Materials (2021) 3(3): 035. https://doi.org/10.21926/rpm.2103035

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

[32] M. Gesoglu, E. Güneyisi, H.Ö. Öz, M.T. Yasemin, I. Taha, Durability and shrinkage characteristics of self-compacting concretes containing recycled coarse and/or fine aggregates. Adv. Mater. Sci. Eng. (2015) 278296. https://doi.org/10.1155/2015/278296

[33] V. Troyan, B. Kindras, Increasing the crack resistance of high-strength self-compacting concrete. Technology Audit and Production Reserves (2021) 1/1(57): 17-24. https://doi.org/10.15587/2706-5448.2021.225500

[34] F. Aslani, S. Nejadi, Shrinkage behavior of self-compacting concrete. Journal of Zhejiang University SCIENCE A (2012) 13(6): 407-419. https://doi.org/10.1631/jzus.A1100340

[35] K. Kovler, O.M. Jensen (Eds) Internal Curing of Concrete, RILEM Report 041, RILEM Publications 2007. https://www.rilem.net/publication/publication/105

[36] D.P. Bentz, W.J. Weiss, Internal Curing: A 2010 State-of-the-Art Review, U.S. Department of Commerce, Gaithersburg, Maryland. 2011. https://doi.org/10.6028/NIST.IR.7765

[37] ACI 231-10 Report on Early Age Cracking:Causes, Measurement and Mitigation, ISBN9780870313592

[38] W. Mahmood, A. Khan, T. Ayub, Mechanical and Durability Properties of Concrete Containing Recycled Concrete Aggregates. Iran J Sci Technol Trans Civ Eng (2022) 46: 2111-2130. https://doi.org/10.1007/s40996-021-00692-x

[39] K. Kapoor, S.P. Singh, B. Singh, Evaluating the durability properties of self compacting concrete made with coarse and fine recycled concrete aggregates. Eur. J. Environ. Civ. Eng. (2020) 24, 2383-2399. https://doi.org/10.1080/19648189.2018.1506825

[40] K/ Kapoor, S. Singh, B. Singh, B. Permeability of self-compacting concrete made with recycled concrete aggregates and metakaolin. J. Sustain. Cem.-Based Mater. (2017) 6: 293-313. https://doi.org/10.1080/21650373.2017.1280426

[41] J. Geng, J. Sun, Characteristics of the carbonation resistance of recycled fine aggregate concrete. Constr. Build. Mater. (2013) 49: 814-820. https://doi.org/10.1016/j.conbuildmat.2013.08.090

[42] N. Roussel, P. Coussot, "Fifty-cent rheometer" for yield stress measurements: From slump to spreading flow, Journal of Rheology (2005) 49: 705-718. https://doi.org/10.1122/1.1879041

[43] G. Hermida, M. Moranville, R.J. Flatt, The role of paste volume on concrete performance. In: Holland TC, Gupta PR, Malhotra VM, editors. Proc. 10th ACI Int. Conf. Recent advances in concrete technology and sustainability issues. Detroit: American Concrete Institute, 2009. 201-14 [SP-261-14].

[44] J. Stark, B. Wicht, Dauerhaftigkeit von Beton. Der Baustoff als Werkstoff. Baupraxis Birkhauser, Berlin, 2001. ISBN 978-3-7643-6344-4. https://doi.org/10.1007/978-3-0348-8301-6_2

[45] F. Sayahi, Plastic Shrinkage Cracking In Concrete : Mitigation and Modelling, PhD dissertation, Luleå University of Technology, Luleå, 2019.

[46] R.V. Silva, R. Neves, J. de Brito, R.K. Dhir,Carbonation behaviour of recycled aggregate concrete,Cement and Concrete Composites (2015) 62: 22-32. https://doi.org/10.1016/j.cemconcomp.2015.04.017

[47] U. Angst, F. Moro, M. Geiker, S. Kessler, H. Beushausen, C. Andrade, J. Lahdensivu, A. Köliö, K.-i. Imamoto, S. von Greve-Dierfeld, M. Serdar, Corrosion of steel in carbonated concrete: mechanisms, practical experience, and research priorities - a critical review by RILEM TC 281-CCC, RILEM Techn Lett (2020) 5: 85-100. https://doi.org/10.21809/rilemtechlett.2020.127

[48] Z. Zhang, P. Trtik, F. Ren, T. Schmid, C.H. Dreimol, U. Angst, Dynamic effect of water penetration on steel corrosion in carbonated mortar: A neutron imaging, electrochemical, and modeling study, CEMENT, (2022) 9: 100043. https://doi.org/10.1016/j.cement.2022.100043

[49] M. Stefanoni, U. Angst, B. Elsener, Kinetics of electrochemical dissolution of metals in porous media. Nat. Mater. (2019) 18: 942-947. https://doi.org/10.1038/s41563-019-0439-8

[50] U.M. Angst, M.R. Geiker, A. Michel, C. Gehlen, H. Wong, O.B. Isgor, B. Elsener, C.M. Hansson, R. Francois, K. Hornbostel, R. Polder, M.C. Alonso, M. Sanchez, M.J. Correia, M. Criado, A. Sagues, N. Buenfeld, The steel-concrete interface, Mater Struct (2017) 50: 143. https://doi.org/10.1617/s11527-017-1010-1

[51] M.C.R. Farage, J. Sercombe, C. Gallé Rehydration and microstructure of cement paste after heating at temperatures up to 300 °C Cem. Concr. Res. (2003) 33: 1047-1056. https://doi.org/10.1016/S0008-8846(03)00005-X

[52] C. Alonso, L. Fernandez Dehydration and rehydration processes of cement paste exposed to high temperature environments J. Mater. Sci. (2004) 39:3015-3024. https://doi.org/10.1023/B:JMSC.0000025827.65956.18

[53] J. Naël-Redolfi, E. Keita, N. Roussel, Water absorption measurement of fine porous aggregates using an evaporative method: Experimental results and physical analysis, Cem. Concr. Res. (2017) 104: 61-67. https://doi.org/10.1016/j.cemconres.2017.11.003

[54] Tests for mechanical and physical properties of aggregates, Determination of Particle Density and Water Absorption, EN 1097-6, 2013.

[55] F. Théréné, E. Keita, J. Naël-redolfi, P. Boustingorry, L. Bonafous, N. Roussel, Water Absorption of recycled aggregates: measurements, artifacts and practical consequences, Cem. Concr. Res. (2020) 137: 106196. https://doi.org/10.1016/j.cemconres.2020.106196

[56] S. Mantellato, M. Palacios, R.J. Flatt, Impact of sample preparation on the specific surface area of synthetic ettringite, Cem. Concr. Res. (2016) 86: 20-28. https://doi.org/10.1016/j.cemconres.2016.04.005

[57] F. Théréné, Granulats poreux et transferts hydriques : mesure , analyse et contrôle, Université Gustave Eiffel, PhD Thesis, 2021.

[58] P. Belin, G. Habert, M. Thiery, N. Roussel, Cement paste content and water absorption of recycled concrete coarse aggregates, Mater. Struct. Constr. (2014) 74: 1451-1465. https://doi.org/10.1617/s11527-013-0128-z

[59] F. Collins, Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint, Int. J. Life Cycle Assess. (2010) 15: 549-556. https://doi.org/10.1007/s11367-010-0191-4

[60] T. Kikuchi, Y. Kuroda, Carbon dioxide uptake in demolished and crushed concrete, Journal of Advanced Concrete Technology (2011) 9(1): 115-124. https://doi.org/10.1007/s11709-020-0635-2

[61] M. Thiery, P. Dangla, P. Belin, G. Habert, N. Roussel, Carbonation kinetics of a bed of recycled concrete aggregates: A laboratory study on model materials, Cement and Concrete Research (2013) 46: 50-65. https://doi.org/10.1016/j.cemconres.2013.01.005