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THE IMPACT OF RECYCLED FINE AGGREGATE ON SELECTED PROPERTIES OF CONCRETE

WPŁYW DROBNEGO KRUSZYWA Z RECYKLINGU NA WYBRANE WŁAŚCIWOŚCI BETONU

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Abstract

The use of recycled fine aggregate in the production of concrete mixes is one of the elements of a circular economy. However, it is important to ensure that such a modification does not significantly affect the durability of the produced concrete elements. One possible criterion to check whether this condition is met is the practical application of the concept of equivalent concrete properties. The presented studies analyzed the properties of concrete with multi-component cement CEM V/A (S-V) and with recycled fine aggregate. The conducted analyses of the research results showed that with a 15% replacement level of natural sand with recycled sand, it is possible to maintain durability characteristics compared to concrete using only natural sand.

Keywords: fine recycled aggregate, concrete durability, equivalent characteristics

Streszczenie

Stosowanie drobnego kruszywa z recyklingu do produkcji mieszanek betonowych jest jednym z elementów gospodarki w obiegu zamkniętym. Należy jednak zwrócić uwagę, aby taka modyfikacja nie wpłynęła znacząco na trwałość wykonywanych elementów betonowych. Jednym z możliwych kryteriów jest sprawdzenie, czy warunek ten jest spełniony, jest zastosowanie w praktyce koncepcji równoważnych właściwości betonu. W przedstawionych badaniach analizowano właściwości betonu z cementem wieloskładnikowym CEM V/A (S-V) oraz z drobnym kruszywem z recyklingu. Przeprowadzone analizy wyników badań wykazały, że przy 15% stopniu zastąpienia piasku naturalnego piaskiem z recyklingu możliwe jest zachowanie cech związanych z trwałością w stosunku do betonu z użyciem wyłącznie piasku naturalnego.

Słowa kluczowe: drobne kruszywo z recyklingu, trwałość betonu, cechy równoważne

1. INTRODUCTION

Currently, many directives and regulations, as well as numerous scientific studies, focus on the carbon footprint [1, 2]. However, increasing attention is being directed towards the circular economy, including the management of the numerous wastes generated from construction and demolition activities [3-5]. Eco-friendly solutions, apart from meeting the goals of the lowest possible carbon footprint and waste management, should ensure the appropriate durability of concrete and the entire structure [6, 7]. The current PN-EN 206 standard partially limits the qualitative or quantitative use of certain eco-friendly solutions, such as the substitution of natural aggregate

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with recycled aggregate in more demanding exposure classes. However, the standard allows for the use of such solutions provided that equivalent performance characteristics are ensured. A beneficial solution, particularly for multi-component cements with low clinker content, is the equivalent test time for non-strength-related tests as included in the national supplement PN-B-06265 to the PN-EN 206 standard. Durability-related characteristics can be verified after a longer period than the standard 28 days, i.e., after 56 or 90 days of curing. A similar relationship is also noticeable when using type II additives, as well as when using type I additives in the form of fine-grained waste materials [8, 9].

The use of fine recycled aggregate is the subject of numerous scientific studies [10, 11]. Mortars modified with fine recycled aggregate can exhibit comparable or even better strength and durability characteristics than those with natural aggregate [12, 13]. The use of processed fine-grained material from crushed aerated concrete elements or ceramic bricks has been found to increase the strength of the mortar and contribute to more effective microstructure sealing, consequently improving durability [12]. Recycled sand is also used as a component in self-compacting concrete mixtures, positively influencing both the rheological and durability properties of this type of concrete [14, 15]. Ensuring durability in many co-existing exposure classes is a complex problem, especially when using concrete mixtures that simultaneously have a reduced carbon footprint and contain waste materials. Therefore, such mixtures should always be considered multi-critically to ensure the appropriate durability of concrete elements while minimizing environmental impact throughout the entire life cycle of the building [16]. The presented studies analyzed the durability-related characteristics, carbonation, and chloride ion migration of low-carbon concrete with fine recycled aggregate from construction debris.

2. MATERIALS AND METHODS

The studies designed five concrete mixtures differing in the level of replacement of natural sand with fine recycled aggregate (FRA), ranging from 0% to 60%. The concrete mix design specifications included: strength class C30/37, consistency class S3 or S4, a maximum aggregate size of 16 mm, and exposure classes: XD1 and XC4. The qualitative selection of concrete mix components included: multi-component cement CEM V/A (S-V) with a strength class of 42.5 N (28-day strength according to PN-EN 196-1 is 58.1 MPa, and 2-day strength is 20.0 MPa) and a net carbon footprint of 323 kg/t, fly ash, gravel aggregate 2/16, crushed dolomite aggregate 8/16, river sand 0/2, and local recycled sand from construction debris (gradation – Fig. 1).

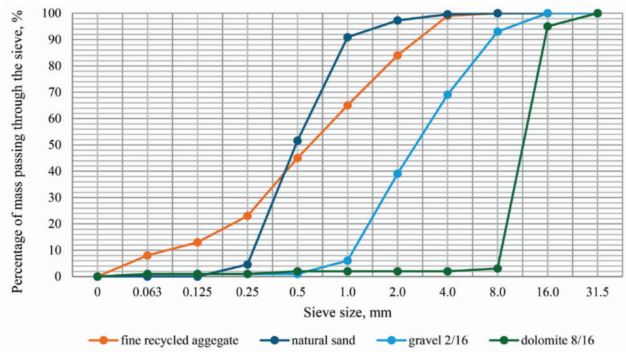

Fig. 1. Aggregate grading

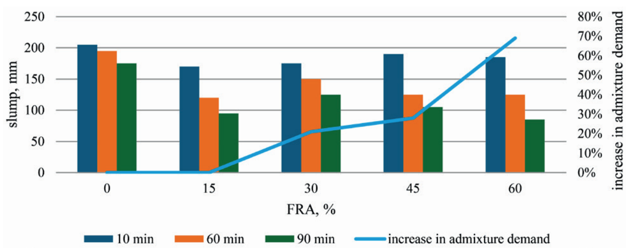

Fig. 2. Changes in consistency over time depending on the proportion of fine recycled aggregate (FRA)

The apparent density of recycled sand grains was 2.59 g/cm³, and its water absorption was 8.2%. The apparent density of natural sand grains was 2.64 g/cm³. Two admixtures from the water-reducing group were used: a plasticizing admixture containing lignosulfonate and gluconate, and a superplasticizing admixture containing modified polycarboxylate ether (PCE) dosed to achieve the desired consistency (Table 1, Fig. 2). The effective water-to-cement ratio was constant for all mixtures and was 0.54.

The preparation of concrete mixes also required the use of a composition of water-reducing admixtures, dosed in varying amounts to achieve the desired consistency. As the proportion of recycled sand increased, it became necessary to increase the dosage of admixtures to obtain a slump of approximately 200 mm. However, maintaining consistency over time was problematic. This was likely due to the significant water demand of the recycled aggregate, as it absorbed water from the concrete mix, resulting in a significant reduction in slump, by as much as two classes, with higher amounts of added recycled aggregate.

Table 1. Compositions per 1 m^3 of analyzed concrete mixtures depending on the proportion of fine recycled aggregate (FRA)

FRA content in sand mass	0%	15%	30%	45%	60%
CEM V/A(S-V), kg	300	300	300	300	300
Fly ash, kg	50	50	50	50	50
Effective water, kg	163	163	163	163	163
Natural sand 0/2, kg	765	641	516	392	285
Fine recycled aggregate, kg	0	114	228	341	439
Gravel 2/16, kg	751	751	751	751	751
Dolomite 8/16, kg	280	280	280	280	280
Plasticizing admixture, kg	1.35	1.35	1.35	1.35	1.35
Superplasticizing admixture, kg	0.946	0.946	1.146	1.200	1.600

The study determined the compressive strength of concrete according to PN-EN 123903, water penetration under pressure according to PN-EN 12390-8, chloride ion migration according to PN-EN 12390-18, and carbonation according to PN-EN 12390-12.

3. RESULTS

The compressive strength of the analyzed concretes was tested at two intervals: after 28 and 56 days (Fig. 3). It was observed that the qualitative change and addition of 15% recycled sand minimally affect compressive strength, especially when analyzing strength after 56 days, which is justified by the use of CEM V/A(S-V) cement. Above the threshold of 30% recycled aggregate content, there is a deterioration in compressive strength, with the difference between strength after 28 days and after 56 days being smaller compared to lower percentages of recycled aggregate. It should be noted that even at the maximum analyzed content of fine recycled aggregate, the achieved compressive strength meets the requirements of class C30/37 after 56 days of curing.

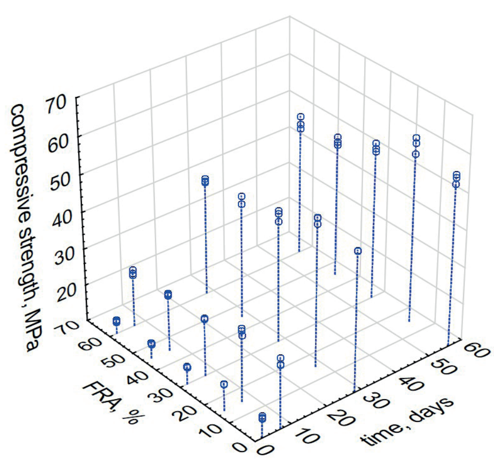

Fig. 3. Development of compressive strength over time depending on the degree of substitution of natural fine aggregate with recycled fine aggregate (FRA)

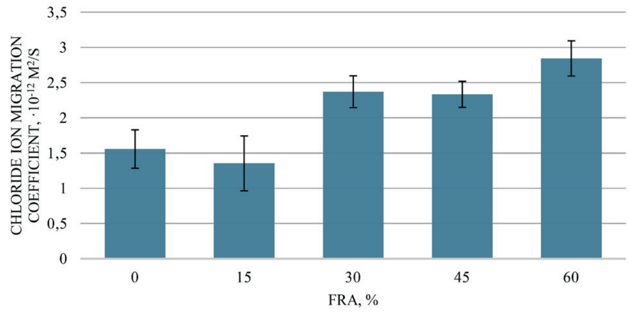

Fig. 4. Chloride ion migration coefficient depending on the degree of substitution of natural fine aggregate with recycled fine aggregate

The chloride ion migration coefficient of the reference composition (without fine recycled aggregate) and the composition with 15% recycled sand differed by less than the standard deviations of the results and were very low, indicating excellent impermeability and resistance to chloride ion penetration. Mixtures with higher proportions of recycled sand had higher chloride ion migration coefficients, ranging from 2.3 to 2.8 × 10^{-12} m^2/s on average, which also indicate good resistance to chloride ion penetration (Fig. 4). The chloride ion migration coefficient can be interpreted as very good below 2 × 10^{-12} m^2/s and as good below 8 × 10^{-12} m^2/s [17].

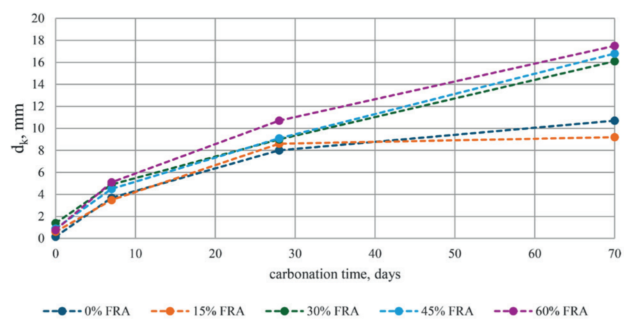

Fig. 5. Depth of carbonation over time depending on the degree of substitution of natural fine aggregate with recycled fine aggregate

The shape and slope characteristics of the depth of carbonation curve over time reflect the susceptibility of concrete to the carbonation process – the steeper the slope, the greater the susceptibility to this process (Fig. 5). It is worth noting that the higher the content of recycled aggregate, the steeper the curve, and the average depth of carbonation increases. This indicates that concrete containing more than 15% by weight of recycled sand has less resistance to carbonation. The curves for compositions containing 30%, 45%, and 60% recycled aggregate respectively resemble a linear function, suggesting that over time, they may become less resistant to the negative effects of carbonation. In contrast, the depth of carbonation for reference samples and those containing 15% fine recycled aggregate shows a slight increase after 30 days (Fig. 5).

The depth of water penetration under pressure can also be considered as a measure of durability (impermeability). The depth of water penetration under pressure increased with an increased proportion of recycled sand. However, for none of the analyzed concretes did it exceed 30 mm, indicating good water tightness of the concrete.

4. CONCLUSIONS AND SUMMARY

Due to the fact that the results of durability characteristics are not straightforward, they have been compiled in tabular form (Table 2) for comparison purposes. This arrangement facilitates comparing the properties of concretes with varying amounts of recycled aggregate relative to the reference composition, which serves as a benchmark. Single upward arrows ↗ indicate a slight increase in the value of a parameter, while double upward arrows ↗ ↗ indicate a noticeable increase. Conversely, downward arrows ↘ indicate a slight decrease, while ↘ ↘ indicate a significant decrease. Arrows on a red background signify worse results in the study compared to the reference sample, whereas green arrows indicate improved properties.

In summary of the presented research results, it can be concluded that substituting natural fine aggregate with recycled fine aggregate at a level of 15% allows achieving durability properties at least equivalent to those of the reference concrete. Therefore, despite the limitation in the dosage of fine recycled aggregate, using it up to 15% can still maintain comparable concrete characteristics. This approach is beneficial due to environmental advantages such as conservation of natural resources. However, it is essential to consider the variability in properties of recycled fine aggregate depending on its origin and processing method.

Table 2. Comparative summary of research results depending on the level of substitution of natural fine aggregate with recycled fine aggregate (FRA)

	Consistency		Compressive strength		Carbonation		Penetration	Chloride ion migration
	Admixture [% c.m.]	Consistency retention [mm]	[MPa]	[MPa]	Depth d_k [mm]	Rate. K_{AC} [mm/√dni]	Depth under pressure [mm]	The chloride ion migration coefficient [· [m²/s]]
Test time	0 min	90 min	28 days	56 days	70 days	70 days	90 days	90 days
FRA 0%	0.77	30	48.0	55.4	10.7	1.29	4	1.56
FRA 15%	–	↗	↗	↗ ↗	↘	↘	↗	↘
FRA 30%	↗	↗	↘	↘	↗	↗	↗	↗
FRA 45%	↗	↗ ↗	↘ ↘	↘	↗	↗	↗ ↗	↗
FRA 60%	↗	↗ ↗	↘ ↘	↘ ↘	↗ ↗	↗ ↗	↗	↗ ↗

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