RECYCLED AGGREGATE CONCRETE FOR RESIDENTIAL STRUCTURES

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ABSTRAKT

Beton s recyklovaným kamenivem nabízí několik příležitostí, jak pozitivně ovlivnit environmentální dopad stavebnictví na životní prostředí. Jeho využití v konstrukcích je však limitované, a to především nižší kvalitou recyklovaného kameniva oproti kamenivu přírodnímu. Výběr vhodných konstrukcí je tak klíčový pro úspěšné uplatnění betonu s recyklovaným kamenivem na stavbách. Sektor bytových staveb nabízí vhodných konstrukcí hned několik. Článek se zabývá možnostmi využití betonu s recyklovaným kamenivem v konstrukcích bytových staveb. Uvádí typické části stavby a požadavky, které jsou na ně kladeny. Tyto požadavky jsou následně porovnány s vlastnostmi betonu a pro jednotlivé konstrukce jsou navrženy možný procentuální obsah recyklovaného kameniva v betonu. V závěru je uveden příklad bytové stavby střední velikosti, u které jsou vyčísleny úspory přírodního kameniva na jednotlivých konstrukcích v případě použití betonu s recyklovaným kamenivem.

KLÍČOVÁ SLOVA

beton s recyklovaným kamenivem • bytové stavby • vlastnosti betonu

ABSTRACT

Recycled aggregate concrete (RAC) offers several opportunities to positively improve the environmental impact of the construction sector. However, its use in construction is limited, mainly because of the lower quality of recycled aggregates compared to natural aggregates. Therefore, the selection of suitable structures is crucial for the successful application of recycled aggregate concrete in construction. The residential construction sector offers several suitable structures. This article analyses the potential of the use of recycled aggregate concrete in residential construction. It lists typical parts of the building and the requirements placed on them. Then these requirements are compared with the properties of concrete and possible percentages of recycled aggregate in concrete are suggested for each structure. Finally, an example of a medium-sized residential building is presented, for which the savings of natural aggregate on individual structures are quantified if recycled aggregate concrete is used.

KEYWORDS

recycled aggregate concrete • residential buildings • properties of concrete

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1. INTRODUCTION

The increasing demand for sustainable construction practices has propelled the construction industry towards innovative solutions that minimise environmental impact while maintaining structural integrity. One such solution that is becoming a standard in the industry is the use of recycled aggregate (RA) in the production of concrete. Using recycled aggregates derived from construction and demolition waste (C&DW) in concrete can conserve a significant amount of natural resources, reduce the demand for landfills and decrease the emissions of CO_2 into the atmosphere.

In contrast to these strong drivers, the use of recycled aggregates poses several challenges. The inferior properties of recycled aggregate concrete (RAC) in comparison with ordinary concrete with natural aggregate (NA) limit its use in a wide range of structures. The greatest influence of RA is on Young's modulus of elasticity which can decrease to 50 % in the case of a replacement ratio of NA by RA 100 %. Another issue of RAC is the uncertain durability of concrete, especially the freeze-thaw resistance, which is highly dependent on the quality of RA and can vary significantly over time.

Due to not only the above-mentioned examples of inferior properties of RAC, the use of RAC in structures is strictly limited. The current version of the European standard EN 206 + A2 for concrete production allows the use of RA only up to 30 % for the exposure classes XC4, XF1, XD1, and XA1, and only in the case where the origin of RA is known. Furthermore, RA must contain more than 90 % concrete particles. Recycled mixed aggregates or recycled brick aggregates can be used only in plain concrete. The Czech complementary standard ČSN P 73 2404 restricts the use of RA even more.

There are numerous types of structures, each designed for a specific purpose and with a distinct set of requirements. Major infrastructure projects such as bridges, dams, tunnels, and civil engineering structures are designed with a minimum lifespan of 100 years. The materials used for these projects must meet the highest quality standards. However, buildings for residential or commercial purposes are designed with considerably lower requirements, and therefore the application of materials with inferior properties is possible. The requirements for residential building structures are often reduced to mechanical properties and durability is required only for exterior structures, which constitute a relatively minor proportion of the project. Small and medium-sized residential buildings offer a significant opportunity to use recycled aggregate concrete and conserve natural aggregate for structures where it is irreplaceable.

2. PROPERTIES OF RECYCLED AGGREGATE CONCRETE

In this section, the properties of the recycled aggregate concrete mixes are presented and compared with ordinary concrete with natural aggregate. The mixes with a 15%, 50%, and 100% content of recycled aggregate were tested. Mixed recycled aggregates with concrete, bricks, mortar, and other material content were used in all mixes. Two fractions were used: a fine fraction 0/8 (fRA) and a coarse fraction 8/16 (cRA). All mixes were designed for strength class C 25/30. The tests were carried out on specimens produced during the production of concrete in a batching plant, and therefore the cement content between mixes could slightly differ over time. The maximum difference between individual mixes was 30 kg.

2.1. Compressive strength

The compressive strength was tested with cubic specimens of an edge length of 150 mm according to CSN EN 12390-3. For each concrete type, more than 30 specimens were tested for compressive strength. Figure 1 shows the results. Natural aggregate concrete (NAC) reports the highest compressive strength. The compressive strength of mixes with a 15% content of fRA and cRA decreased by 8% and 6%, respectively, compared to the NAC. The compressive strength of mixes with a 50% content of fRA and cRA decreased by 14% and 11%, respectively, compared to the NAC. Lastly, mixes with a content of 100% RA reported a decrease in compressive strength of 22% on average. Fine recycled aggregate decreases the compressive strength of concrete more than coarse recycled aggregate.

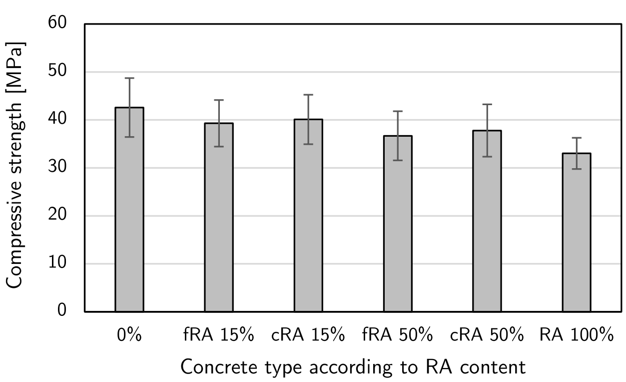

Figure 1: *Cubic compressive strength of concrete with different RA content.*

2.2. Depth of penetration of water under pressure

The depth of penetration of water under pressure was tested with cubic specimens with an edge length of 150 mm according to standard ČSN EN 12390-8. For each type of concrete, more than 10 specimens were tested. Figure 2 shows the results that report a higher variance between all the tested mixes. Mixes with a 100% RA content reported the highest depth of penetration of water than mixes with a lower RA content. RA content up to 50% does not have a significant impact on the watertightness of the concrete. All mixes meet the requirements of ČSN EN 206+A2 on water penetration limit for each exposure class.

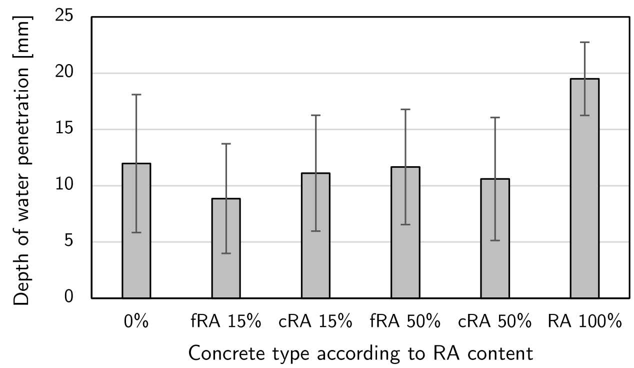

Figure 2: *Depth of penetration of water under pressure of concrete with different RA content.*

2.3. Young's modulus of elasticity

The modulus of elasticity was tested with cylinder specimens with diameter of 150 mm and height of 300 mm according to standard ČSN ISO 1920-10. The modulus of elasticity is the most influenced property of concrete with an increase in the content of RA in the mix. Figure 3 shows similar trends that can be observed for the results of the compressive strength of concrete. The modulus of elasticity of the mixes with a 15% content of fRA and cRA decreased only by 4% and 2%, respectively, compared to the NAC. However, the modulus of elasticity of the mixes with a 50% content of fRA and cRA decreased by 45% and 39%, respectively, compared to the NAC. Lastly, mixes with a content of 100% RA reported a decrease of 55%. As with compressive strength, coarse recycled aggregate has a lower impact on modulus values.

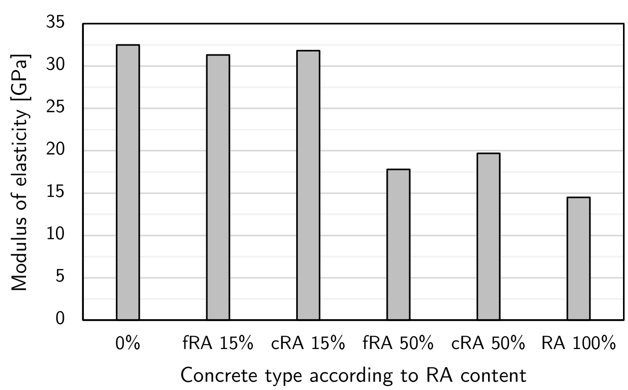

Figure 3: *Modulus of elasticity of concrete with different RA content.*

2.4. Bond strength

The bond strength was tested with cubic specimens with an edge length of 150 mm according to standard ČSN 73 1333. For this test, only three mixes were tested with three specimens for each mix. The results in Figure 4 do not correspond to the usual trend. Mix with 50% of cRA reports a higher bond strength than NAC. The mix with 100% of RA reports a lower bond strength. The results should be verified in future research.

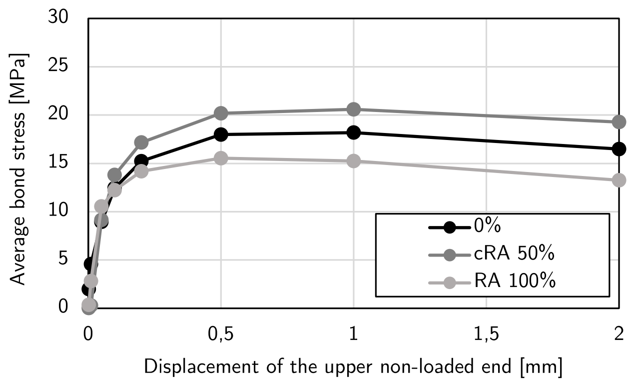

Figure 4: *Bond strength of concrete with different RA content.*

Figure 5: *Test boreholes from bored piles made of recycled aggregate concrete containing* 50% *recycled aggregate.*

3. CONSTRUCTION PARTS OF RESIDENTIAL BUILDINGS

This section lists typical components of residential buildings and the requirements that are placed on them. These requirements are then compared with the properties of RAC and the recommended RA content is proposed with two different approaches of the design. The first approach is more conservative and suggests a lower RA content in concrete in relation to the safer side of the building design. The second approach is progressive and suggests a higher RA content in concrete. Structures designed using the progressive approach will still meet the requirements while conserving more natural resources than the conservative approach, but the unstable properties of RA must be taken into account during the design process.

3.1. Deep foundation - bored piles

The typical concrete specification for bored piles of medium-sized residential buildings is the strength class C 25/30 or C 30/37 and the exposure classes XA1 to XA3. The highest demands are placed on the properties of fresh concrete. During concrete pouring, the water must not be separated by the high pressure generated by the height of the pile. Recycled aggregate concrete tends to contain a greater proportion of water due to the higher water absorption of the aggregate and therefore may be more prone to bleeding than ordinary concrete. Previous research has indicated that a 50% RA content in concrete for bored piles is a safe amount that does not cause bleeding of the concrete or the segregation of lighter particles contained in RA (see Figure 5). The recommended content of RA in concrete for bored piles is therefore 30% to 50%.

3.2. Base concrete

The main purpose of the base concrete is to level the ground and create a stable surface on which to lay the foundation plate reinforcement. The requirements for the base concrete are minimal. Typically, a C 8/10 or C 12/15 strength class is specified with no additional exposure classes. The RA content in the base concrete can be up to 100%, although in practice it is generally limited to 50%.

3.3. White tank - foundation plate and perimeter walls

The term "white tank" is used to describe the underground part of a building where waterproofing is achieved through the use of a watertight concrete structure, comprising the foundation plate and the perimeter walls. This method of waterproofing differs from the addition of a separate layer of waterproofing material. In addition to the watertightness of the concrete itself, which is evaluated by the depth of penetration of the water under pressure, the second crucial attribute of watertight concrete is shrinkage, which is responsible for the formation of cracks in the structure. Although the RAC water penetration values are comparable to those of ordinary concrete, the increase in drying shrinkage caused by the higher water content in the RAC is more significant. Higher shrinkage can lead to the excessive development of cracks that are unacceptable for this type of structure. Therefore, the RA content for watertight concrete structures is limited to a maximum of 15%.

3.4. Horizontal load-bearing structures

The design of a horizontal load-bearing structure, such as slabs, purlins, and beams, is primarily determined by the maximum allowable deflection of the structure. The greatest influence on the deflection is the Young's modulus of elasticity, which decreases significantly with an increased content of RA in concrete. The addition of 50% and 100% RA to concrete can reduce the modulus by up to 30% and 50%, respectively. Consequently, the content of RA in concrete for horizontal load-bearing structures is conservatively limited only to 15%. However, the values of Young's modulus of elasticity of concrete with a 30% RA content remain comparable to those of ordinary concrete, and therefore it can be recommended for specific cases with lower loads.

3.5. Vertical structures

Vertical load-bearing structures such as perimeter walls and elevator shafts, or non-load-bearing structures such as partition walls, have minimum material requirements in terms of mechanical properties and durability. The most limiting factor is the lower specific density of concrete due to the lower specific density of RA. The standard requirements for airborne sound insulation of residential buildings are quite stringent. Partition walls with an optimised design combined with the lower specific density of RAC do not have to meet the standard requirements in specific cases.

Table 1: *Potential savings of natural aggregate replaced by recycled aggregate on a medium-sized residential building project*

Type of structure	Amount of concrete (m^3)	Amount of aggregate (t)	Conservative approach *	Conservative approach **	Progressive approach *	Progressive approach **
Exterior structures	600	1.050	0 %	0	15 %	160
Vertical structures	1.700	2.975	50 %	1.490	100 %	2.975
Horizontal load-bearing structures	3.100	5.425	15 %	815	30 %	1.630
White tank - foundation plate, perimeter walls	1.400	2.450	0 %	0	15 %	360
Base concrete	300	5.25	50 %	265	100 %	525
Deep foundation - bored piles	950	1.665	30 %	500	50 %	830
Total	**8050**	**14.090**		**3.070**		**6495**

* Percentage substitution of natural aggregate by recycled aggregate
** Amount of natural aggregate saved in tonnes

However, previous research conducted on partition walls between two apartment units with 100% RA content has shown that it is possible to use RAC for this type of structure and meet the requirements of current standards. Therefore, the recommended RA content for most vertical structures is 50%, but a content of 100% is also feasible for many structures.

3.6. Exterior structures

Structures such as attics, balconies, and retaining walls are exposed to the external environment, and freeze-thaw resistance plays an important role in the longevity of these structures. Previous research on RAC freeze-thaw resistance has not always confirmed that RAC has sufficient freeze-thaw resistance. This may be mainly due to the unstable quality of RA. For this reason, the RA content in concrete for exterior structures is limited to 15%.

4. EXAMPLE OF RA UTILISATION ON A MEDIUM-SIZED RESIDENTIAL BUILDING

In this section, an example of a medium-sized residential building developed in recent years in Prague is used to illustrate the potential savings in natural aggregate required for concrete production if it is replaced by recycled aggregate during the construction process. The volume of cubic metres of concrete for individual construction parts is based on the original project. The figures are rounded for the sake of clarity. Firstly, the amount of aggregate needed for the production of concrete is quantified. An average of 1750 kg was accounted for one cubic metre of concrete. Consequently, conservative and progressive approaches from the previous section are applied for each construction part and the absolute amount of natural aggregate saved is also quantified. The exact figures can be found in Table 1.

Slabs represent the largest proportion of concrete. Unfortunately, the use of RA for this type of structure is severely limited due to low Young's modulus values, and therefore only a small proportion of NA can be saved. Vertical structures are the second most represented and offer the largest possible savings. Other construction parts contribute only a small proportion of the total concrete volume, or the use of RA very limited, as in underground watertight structures.

In the case of the conservative approach, approximately 3,070 tonnes of NA could be saved by using RA, which represents 22% of the total aggregate mass required for the project. In the case of the progressive approach, up to 6,495 tonnes of aggregate could be saved, representing 46% of the total aggregate mass.

5. CONCLUSION

The properties of RAC are influenced not only by the quality of RA but also by the quantity of RA present in the concrete. An increase in the proportion of RA in concrete results in a deterioration of its properties. In order to facilitate the widest possible use of RAC in building structures, the quantity of RA in concrete can be adjusted according to the specific type of concrete construction. The aforementioned approaches suggest different RA contents in concrete for various residential structures. The conservative approach suggests a lower RA content, which is a safer option. The progressive approach, in contrast, advocates for a higher RA content in concrete. The conservative approach to the use of RAC in medium-sized residential buildings has the potential to save up to 3,000 tons of natural aggregate. In the case of the progressive approach, the potential reduction in the use of natural aggregate is up to 6,500 tonnes. The construction of the Dvorecký Bridge in Prague is estimated to consume approximately 32,500 tonnes of aggregate. In order to save enough natural aggregate for the construction of Dvorecký Bridge, approximately eleven medium-size residential buildings would have to be built with the conservative approach to the design as suggested in the previous sections. In the case of the progressive approach, only five buildings would save enough natural aggregate for the new bridge. By employing RAC in structures with lower demand for the quality and durability of materials, natural aggregate can be conserved for construction projects where it is irreplaceable.

ACKNOWLEDGEMENTS

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS23/034/OHK1/1T/11.

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