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Relationship between the compressive and flexural tensile strength of recycled aggregate concrete containing waste perlite powders

TDK Research

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Abbreviations

OPC	ordinary Portland cement
NA	natural aggregate
RCA	recycled concrete aggregate
RR	replacement ratio
FA	fine aggregate
SCM	supplementary cementitious material
WPP	waste perlite powder
WPP-SZ	fine waste perlite powder from cyclone filtration
WPP-C	coarse waste perlite powder from the baghouse
RAC	recycled aggregate concrete
PD	packing density
FR	fine recycled aggregate
FN	fine natural aggregate
CR	coarse recycled aggregate
CN	coarse natural aggregate
SP	superplasticiser
RH	relative humidity
SAI	strength activity index

Abstract

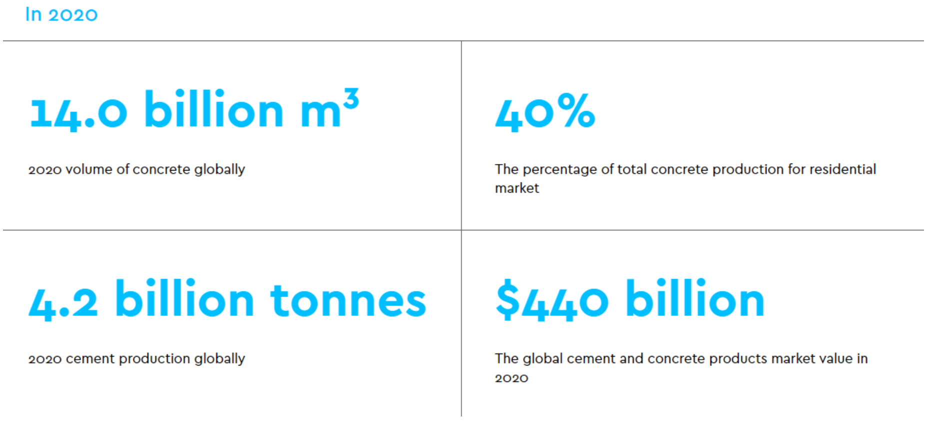
This study investigates the mechanical performance of recycled aggregate concretes containing waste perlite powders as supplementary cementitious materials. The mechanical performance of conventional and sustainable concretes can be quite different and is influenced by the type of raw materials used, their dosage and, most importantly, particle packing. Recycled aggregates come in many varieties, but their recent application has been limited mainly to coarse fractions. Moreover, natural sources of concrete's raw materials are waning, which leads to economic, environmental and technical concerns. One of the leading contributors to the environmental burden of concrete is cement production, predominantly due to the high levels of carbon dioxide emission.

In order to address above listed limitations in sustainable concrete development, a concrete mix design based on the particle density approach was followed. Two types of alternative materials were utilised: fine and coarse recycled aggregate fractions for replacing natural aggregate, and waste perlite powders as supplementary cementitious materials for replacing ordinary Portland cement. In addition, a relationship between the compressive and flexural tensile strengths of developed mixes was investigated and compared with the proposed models in respective technical literature. The relationship is a significant milestone for applying alternative concretes in practice, because it is one of the most common approaches that concrete producers and designers adopt to estimate concrete's tensile strength.

1. Introduction

1.1 Recycled concrete

The construction industry could hardly exist today without concrete. Highly diverse, versatile and easy to use, concrete has been one of the primary construction materials since the Industrial Revolution. Over 4 billion tonnes have been produced only in 2020 [1. Figure], and these amounts are expected to grow, according to the Global Cement and Concrete Association. The production of ordinary Portland cement (OPC), the primary binder of conventional concrete, is demanding to the environment due to the high carbon dioxide emission and significant energy consumption. Mining and refining the natural aggregate (NA) used in concrete requires enormous amounts of energy and manpower [1]. Therefore, multiple ideas have been put forward to replace or reduce both OPC and NA content without significantly worsening the properties of concrete.



1. Figure *Annual production values of concrete for 2020 [2]*

1.2 Alternative aggregates

Recycled aggregate comes from construction and demolition waste and mainly consists of crushed concrete, brick, mortar or even glass. Concrete waste can be used as recycled concrete aggregate (RCA), but it is not always advantageous, especially for higher-quality structural concrete [3]. The concrete waste consists of the original natural aggregate with attached mortar, so it is not a homogenous material. It is more porous than NA and absorbs more water [4] [3], so complete replacement by this material has been recognised as impossible in high-quality, durable concrete. Some researchers observed the optimal replacement ratio (RR) to be at 30% [5]. The on-spot separation of mortar from aggregate is not always feasible, and it might be costly. Alternatively, many researchers proposed the pre-treatment of RCA, either by pre-soaking in acids [3] or inducing brittleness and lower fracture energy by microwave heating [6]. Many proposals have been put forward concerning alternative aggregates, with cost, availability, and ease of transport being the most important aspects. For example, polishing waste from granite was used effectively as fine aggregate (FA) [7], but other types of construction wastes, such as mortar, bricks, or glass [8] and even organic materials, like palm kernel shell [9] are also proven to be effective alternatives to NA, although their refinement on industrial scale is yet to be developed. Some artificial aggregates, expanded clay or expanded perlite for instance, can be utilised for lightweight aggregate concrete production. Of course, these aggregates should be further investigated to explore their full potential, therefore in this study, RCA-based concretes will be used.

1.3 Alternative cementitious materials

A wide range of experiments were conducted concerning supplementary cementitious materials (SCMs) replacing OPC. These cementitious replacements are typically recognised as effective regarding the packing density approach and the filler/occupant effect. The particle size of SCMs is generally between the size of cement particles and aggregates, but they can also be finer than cement, such as in the case of metakaolin or silica fume. This way, they fill in the voids (filler effect) between larger particles, resulting in the need for less cement and entrapped air. On the other hand, the occupant effect refers to the filling of the porous volume between smaller particles by the coarser ones. The volumetric ratio of solid volume to the whole volume of the concrete is called packing density, which should be considered when optimising RRs. Some SCMs demonstrate a pozzolanic effect, meaning that they are not inert and actively participate in the setting of concrete through a pozzolanic reaction. Hydraulic SCMs have the ability to bind concrete constituents together when mixed with water [10]. Normally, SCMs also have a lower carbon footprint than OPC [1]. Hence, other than having a positive influence on the environmental burden of cement, SCMs have been utilised as enhancers of cementitious materials' properties.

Commonly used SCMs are mostly industrial byproducts with a few exceptions (e.g. metakaolin) that are widely available and otherwise considered waste. Some of the most common SCMs are fly ash, blast furnace slag, metakaolin, silica fume, etc. Fly ash [11] [12] [13] is an airborne residue from coal combustion processes, which can demonstrate both pozzolanic and hydraulic properties depending on the physical structure and chemical composition of the material [14]. Blast furnace slag [4] is also hydraulic but reacts slower than OPC. Granulated blast furnace slag is obtained from the process of iron production, where it is tapped off as a reduction waste. The molten slag is quenched with water, resulting in a composition similar to OPC [14]. Metakaolin and silica fumes are finer than cement and highly pozzolanic [15]. Silica fume is gained during the production of silicon alloys in arc furnaces [14]. In contrast, metakaolin is a result of the thermal treatment or calcination of kaolin, an important resource used by the ceramics industry [16].

Due to the reduction of resources and lower availability of conventional SCMs in some regions, recent research has been focused on locally abundant alternative solutions. Many researchers found the use of ground demolition waste, such as recycled concrete powder and recycled brick powder, as SCMs feasible as well [17] [18] [19] [20] [21] [22] [23]. These materials are widely available and easy to procure. Another source of SCMs is mining and refining activity, such as granite polishing waste [7], which was successfully used as SCM. Hence, in this study, waste generated through perlite production has been investigated as SCM due to its availability in Hungary.

Perlite refining and expansion is an industrial process that produces fine waste powder, formerly deposited with no applications whatsoever. Waste perlite powder (WPP) [17] [18] [24] [25], however, is a possible cementitious material with a lot of good prospects, especially in Hungary, where perlite is abundant. In the samples produced for the experiment, WPP was used to replace OPC.

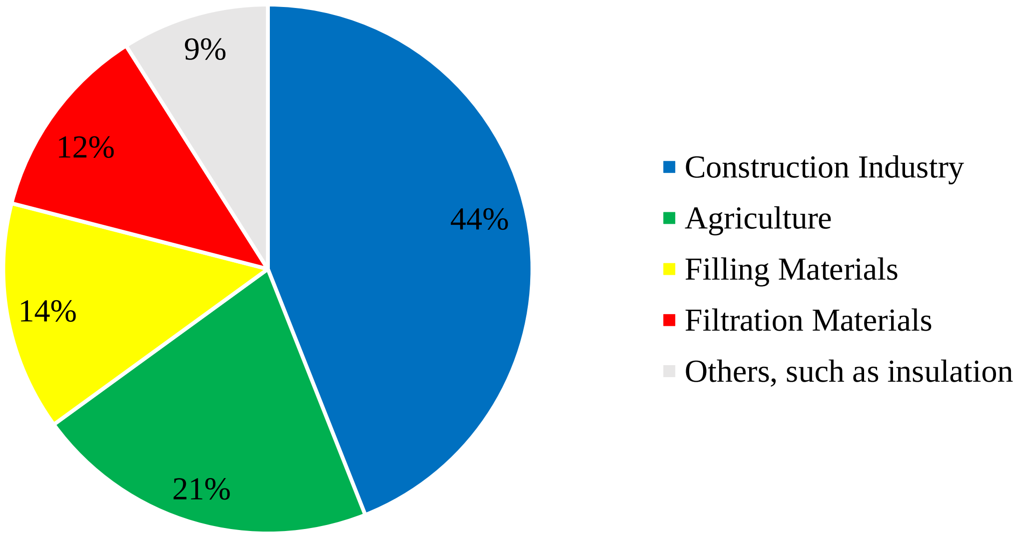
1.4 An overview of the perlite industry in Hungary

Perlite is a type of volcanic glass with spherical, pearl-like microstructure containing high amounts of silicic acid [2. Figure]. Concerning chemical properties and composition, perlite is similar to obsidian and rhyolite, but these rocks differ in water content. Hungarian perlite deposits and formations originate from tertiary volcanic activity [26].

2. Figure *Natural perlite rock [27]*

When heated above 1000-1200°C, the particles develop plastic properties; the water content evaporates, resulting in volumetric expansion [3. Figure]. Expanded perlite possesses excellent thermal- and sound-insulating properties and good fire resistance. The applications of expanded perlite range from the construction and chemical industry to agriculture [26] [4. Figure].

3. Figure *Expanded perlite [28]*



4. Figure *Expanded perlite use per industrial branches [29]*

During the refining process and expansion of natural perlite, a large quantity of perlite waste is formed. The crushing and subsequent grading of perlite yields materials of different particle sizes: coarser perlite can be used for expansion, but the finer substance separated by various types of filters is considered waste, which is utilised in this study as well [30]. Another source of WPP is expansion. Overall, the quantity of waste can amount to more than 10% of the mass of expanded perlite gained [31]. Both types of industrial waste consist of very fine particles, and since it cannot be further used, it is usually deposited outdoors, sometimes resulting in pollution as well. The fine microstructure and high silica content allow WPP to be used as SCM in concrete [31].

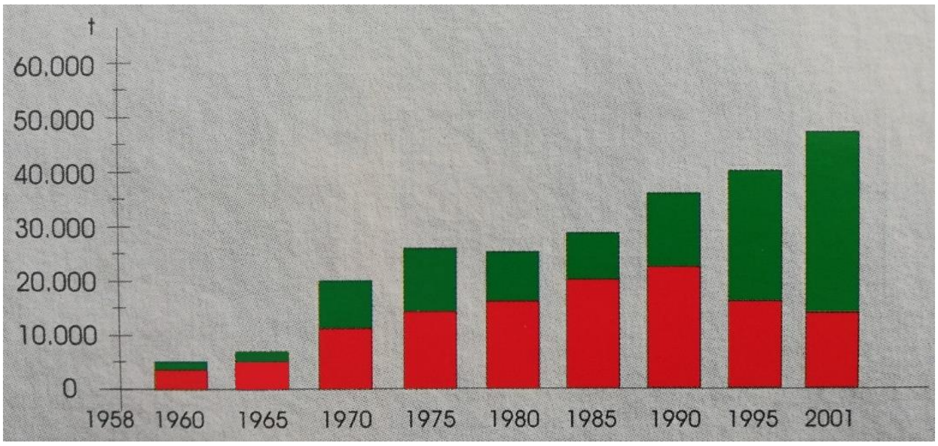
Hungary has rich perlite deposits, the most important of which are located at *Pálháza*. Two other mines, one at *Telkibánya* and the other at *Bózsva* were also opened, but now only *Pálháza* and *Bózsva* operate. After drying, grinding and sieving, it is transported to expanding facilities on rail or roads. Expanding facilities operate in *Dorog, Pilisvörösvár, Tököl, Lepsény, Erdőbénye* and *Olaszliszka* [26].

The *Pálháza* deposit is in the northeastern section of the *Tokaj* mountain range, and it originates from the late Miocene stage. During the geological survey, a rhyolitic caldera structure has been discovered in the vicinity of the mine. In the caldera's edge, perlite bodies can be found. Local perlite has been formed from obsidian-rich rhyolitic lava; its crystalline content is low (6%), whereas its water content is around 3%. In the last 50 years, more than 3.5 million tonnes were mined here [26].

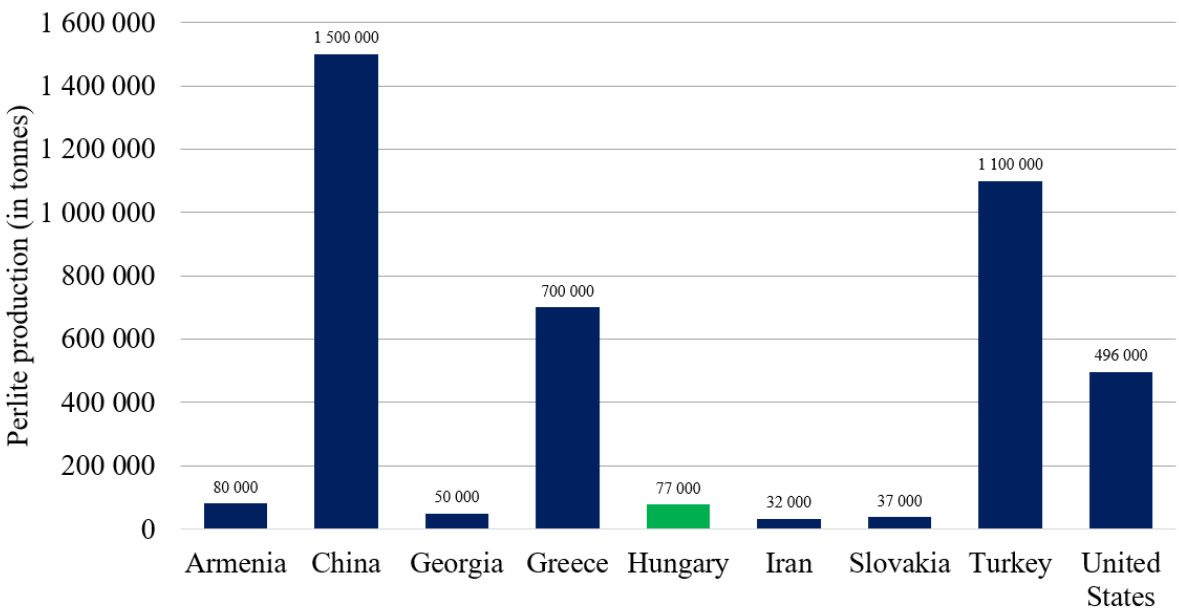
After World War II, international and Hungarian researchers began studying perlite and its possible uses in the construction industry. The war caused the massive destruction of residential buildings, and it was thought that perlite would be an efficient replacement for the then-scarce Portland cement in the grand-scale construction of new housing estates [26].

It was a novel material because perlite expansion was only developed in the 1940's. Hungary was among the first to conduct such experiments because the capabilities of perlite concrete were recognised by the ÉAKKI (Építőanyagipari Központi Kutató Intézet). The first expansion was done in 1951-52 at the Budapest University of Technology while geologists were already mapping the perlite deposits around *Pálháza* and *Telkibánya*. The mine at *Pálháza* opened in 1959 [5. Figure] and soon was expanded to keep up with the demand. In 1988, the mine yielded 120,000 tonnes of raw perlite and the same amount of ground perlite. Although there was a recession in production since, there was still a yearly output of 60 000 tonnes until 2010, of which 65% was exported [6. Figure]. From then on, a steady increase can be observed. Hungary is nowadays among the top producers of this material in the world [7. Figure] [26].

5. Figure *The perlite mine at Pálháza [32]*



6. Figure *Hungarian perlite production (in red) and export (in green) between 1958 and 2001 [26]*



7. Figure *Perlite production per country in 2021, in tonnes [33]*

1.5 Perlite as supplementary cementitious material

In this research, two types of WPPs were used as SCMs with various replacement rates. Although many researchers have dealt with perlite so far, there are still many opportunities in this material to be uncovered. Most experts noted the pozzolanic nature of the material and the increased water demand for concretes containing WPPs. Dacić and Fenyvesi [17] investigated the WPP mixes through the wet packing approach and showed that WPP is a valid material for cement replacement concerning its mechanical abilities. Moreover, based on the mortar samples containing 15, 30 and 45% of separate WPP-C and WPP-SZ (i.e., two types of WPPs used in this research as well) as SCMs, Dacić et al. investigated the strength activity index of the samples. They observed that WPP-SZ, as a finer WPP, is more effective in pozzolanic activity and that the replacement should be limited to 15% for both WPPs [18].

Moreover, Erdem et al. [24] studied blended types of cement containing perlite as a pozzolanic addition and noted that the compressive strength of cement was higher when the components were blended and ground together than when they were ground separately and mixed thereafter. The grinding of perlite powder is easier and requires less energy than in the case of OPC clinker. Karein et al. [34] investigated the transport capabilities of concrete made with pre-treated and milled natural perlite SCM and discovered that perlite inclusion improves mass transport properties. Fodil and Mohamed [35] substituted cement with perlite and pozzolana and studied their effects on concrete's mechanical strength and corrosion resistance. They observed that these SCMs can improve the mechanical abilities of concrete, but the concrete was less resistant to corrosion in aggressive environments.

According to El-Mir et al. [36], who produced blast furnace slag and WPP composite mortars, WPP replacement prolonged the setting time and decreased the durability, but the compressive strength of their mortar was also higher. Mortars were also the field of research of Stefanidou et al. [31], who concluded that the partial or even total substitution of natural pozzolan by perlite can positively influence the mortars' mechanical properties. Ramezanianpour et al. [25] researched high-quality concrete and asserted that calcinated perlite powder is a valid SCM in this field. Since self-compacting concrete is a highly effective building material used for large-scale constructions, many researchers opted to uncover the possibilities of using perlite powder in this regard too [37] [38] [11] [39]. Based on the literature review, the feasibility of perlite as pozzolana has been recognised, but its application as SCM is still limited.

1.6 Relationship between compressive and flexural tensile strengths

The main goal of this study is to investigate the relationship between the compressive and flexural tensile strengths of concrete containing WPPs as SCMs and RCA as both coarse and fine aggregate. Tensile strength, let it be splitting or flexural, is not just a theoretical approach to concrete design but also a practical one: tensile strength values are widely used when calculating shear, cracking, bond and anchorage, as well as prestressed elements and reinforcement design. The parameter is often used by concrete producers and designers worldwide. Standards such as Eurocode-02 give comprehensive formulae for the relationship between the tensile and compressive strength of conventional concretes. These were, however, created with conventional raw materials in mind, but according to the researchers, the equations are also quite applicable to sustainable concretes with minor changes. [40].

Recycled aggregate concrete (RAC) has been a field of interest of many researchers in the past 40 years, and its profile is becoming increasingly complex. To that end, many recommend that new variables should be considered when describing the mechanical performance of such concretes. Silva et al. [40] produced a comprehensive literature review in this regard concerning failure modes, aggregate shape, mineral additions and replacement rate, based on which new coefficients were produced.

According to the researchers, the failure mode of RAC is predictable and mostly initiated through the largest crack oriented in the direction normal to the applied load. The shape of aggregate particles also influences failure modes and mechanical properties. Concretes produced with different types of RA - which exhibit similar physical behaviour regardless of size - will likely perform similarly. The compressive and tensile strengths of RAC are furthermore influenced by the quality of its RCA fractions [40].

It is universally accepted that with higher replacement rates, the mechanical properties of RAC degrade. Experiments were conducted with RAC made with SCMs too. In these cases, SMCs were fly ash, granulated blast furnace slag and metakaolin. SCM replacement usually involved a decrease in tensile strength, although RAC made with 50% blast furnace slag binder mix actually improved tensile strength by 20% [41]. Therefore, blast furnace slag replacement in conventional concrete and RAC can yield similar, if not better results. These results demonstrate that combining RCA with SCMs can be beneficial for concrete in terms of mechanical properties, aside from the economic and environmental advantages [40].

Research concerning the strength ratios of perlite-based recycled concrete is limited. However, Yu et al. [42] showed that concrete strength is closely related to perlite powders' pozzolanic reactivity. Multiple models exist for the relation between concrete's flexural tensile and compressive strength, most of which can be found in the respective standard (e.g. EN 206). The relationships developed in the standards and literature based on conventional concrete containing alternative materials as SCMs and aggregate, to the author's knowledge, are presented in [1. Table].

1. Table *Comparison of different models developed for the compressive-flexural relationship in conventional and recycled concretes*

Source	Relationship	Short description
IS: 456-2000 [43]	$f_{fl} = 0.7 \cdot \sqrt{f_c{'}}^{*1}$	Indian standard for conventional concrete
ACI 318 [44]	$f_{fl} = 0.62 \cdot \sqrt{f_{ck}}^{*2}$	United States standard for conventional concrete
Eurocode-02 [45]	$f_{fl} = 0.201 \cdot f_c$	European standard for conventional concrete
Kępniak and Woyciechowski [46]	$f_{fl} = 0{,}402 \cdot \sqrt{f_{ck}{'}}^{*3} - 0{,}028 \cdot \sqrt[3]{f_{ck}{'}^2} + 0{,}005 \cdot f_{ck}{'} \left(\frac{w}{c}\right)^{*4} - 0{,}007 f_{ck}{'} \left(\frac{c}{w}\right)^{*5}$	Model for high-performance concrete.
Khatab et al. [47]	$f_{fl} = 0.084 \cdot f_c^{*6} + 1.039$	Recycled aggregate concrete with recycled aggregate having mixed origin (i.e., natural aggregate, crushed concrete, crushed ceramic, bitumen and glass).
Elinwa and Kabir [48]	1. $f_{fl} = 0.8 \cdot \sqrt{f_c}$ 2. $f_{fl} = 0.49 \cdot \sqrt[3]{f_c^2}$	Hospital waste ash concrete.

Evin and Rachmansyah [49]	$f_{fl} = 0.447 \cdot \sqrt{f_{ck}}$	Geopolymer concrete utilising fly ash as a precursor.
Waqas et al. [50]	$f_{fl} = 0.25 \cdot \sqrt[3]{{f_c}^2}$	Geopolymer concrete utilising blast furnace slag and fly ash as precursors.

*1	${f_c}'$	-	characteristic cube compressive strength
*2	f_{ck}	-	average/mean cylinder compressive strength
*3	${f_{ck}}'$	-	characteristic cylinder compressive strength
*4	$\frac{w}{c}$	-	water/cement ratio
*5	$\frac{c}{w}$	-	cement/water ratio
*6	f_c	-	average/mean cube compressive strength

In some models, flexural tensile strength is taken as 10% of compressive strength, while others use polynomials or other nonlinear approximations [1. Table]. According to Kępniak and Woyciechowski [46], standards overestimate splitting tensile strength for conventional concrete, and other factors should also be taken into account as constants, like water-cement (W/C) ratio, air content, etc. Zhang et al. [51] mentioned that recycled concrete's damage process is similar to conventional concrete made with OPC and NA. Interesting models have been developed by Khatab et al. for RAC [47]. However, a range of models are developed based on empirical data of various types of sustainable solutions. Yusuf et al. [9], for example, studied concrete made with palm kernel shells originating as waste from the palm oil industry, while Elinwa and Kabir [48] studied hospital-waste-based concrete. For geopolymer concretes Evin and Rachmansyah [49], Waqas et al. [50], Hamidi et al. [52], and Phoo-ngernkham et al. [53] each established their new models. Hence, in this study, the models developed to date will be assessed for applicability to the empirical data gathered on RAC with WPP as SCM.

2. Research methodology

2.1 Materials and mix design

For the cementitious materials, OPC of CEM I. 42.5 N grade type was used, supplemented by two WPP types with a difference in their specific surface areas (SSA, measured with the Blaine method) and particle sizes. The finer WPP was abbreviated as WPP-SZ, and the coarser as WPP-C [8. Figure]. The two blended cements were produced as shown in [2. Table] based on the RRs of cement by WPP. The physical properties of used cementitious materials are shown in [3. Table]. In the previous investigation [54], wet packing density (PD) was used to determine the optimal ratio of WPPs, where RRs of 2.5% by volume of cement by each WPP and 5% showed the most beneficial results. The PD data shown in [2. Table] is representative of chosen optimal ternary blended cements if the PD of OPC is 0.622.

2. Table *Replacement ratios and packing densities of waste perlite powders*

Blended cement	*RR by WPP-SZ [%]*	*RR by WPP-C [%]*	*Packing density [-]*
SZ2.5 – C2.5	2.5	2.5	0.638
SZ5 – C5	5	5	0.643

8. Figure *Waste perlite powders*

3. Table *Physical properties of the cementitious materials used*

Type of cementitious material	Density, in g/cm^3	Specific surface area, in m^2/kg
Ordinary Portland cement (OPC)	3.19	396
Waste perlite powder, fine (WPP-SZ)	2.43	1132
Waste perlite powder, coarse (WPP-C)	2.43	176

On the other hand, the aggregate mixtures consisted of four types of aggregates: coarse natural (CN), fine natural (FN), coarse recycled (CR) and fine recycled (FR) [9. Figure] whose characteristics can be seen in [4. Table]. Aggregate mixes containing all four aggregate types were chosen with the PD optimisation method, similar to the cementitious mix design mentioned above. It was experimentally shown that three aggregate combinations had PDs equal to 0.695. Hence, these three mixes of aggregate were used in the concrete mixes for further investigation:

- *CR4-CN6 – FR1-FN9*
- *CR3-CN7 – FR1-FN9*
- *CR2-CN8 – FR2-FN8*

Designations of aggregate mixes consist of the previously explained abbreviations plus the numerical notation, which represents the ratio of specific aggregates in the respective group. Numerical notation after CR is the ratio of recycled aggregate utilised in the coarse aggregate mix on a scale of 10. For instance, CR2-CN8 shows that 20% of the coarse aggregate mix consists of RA, whereas the other 80% is NA. The same applies to the fine aggregates. For simplification, the following designations have been adopted, respectively:

- *RC4 – F1 (i.e., CR4-CN6 – FR1-FN9)*
- *RC3 – F1 (i.e., CR3-CN7 – FR1-FN9)*
- *RC2 – F2 (i.e., CR2-CN8 – FR2-FN8).*

4. Table *Characteristics of aggregates used*

Type of aggregate	Oven-dried density, in g/cm^3	Water absorption, in m%	Saturated-surface-dry (SSD) density, in g/cm^3
Coarse natural (CN)	2.39	3.6	2.48
Coarse recycled (CR)	2.55	1.1	2.58
Fine natural (FN)	2.16	8.2	2.34
Fine recycled (FR)	2.59	0.7	2.61

9. Figure *The aggregates of the experimental concrete. Clockwise, from top left to bottom left: coarse natural aggregate, coarse recycled aggregate, fine recycled aggregate and fine natural aggregate*

The concretes used for testing were designed with a water-to-binder ratio by mass of 0.4. The applied superplasticiser (SP) was Viscocrete 5 Neu, with a density of 1.1 g/cm^3. Since the PD of aggregate phases was 0.695, the cement paste volume was 0.305 in the concrete mix design. Based on the three aggregate mixtures and three cementitious mixes (i.e., one made only with OPC, which is to be referred to as a control mixture), in total nine concretes were produced. The name of these mixtures is created from the aggregate mixture (RCa - Fb) and the cementitious mixture (CMn), where a, b and n are the replacement ratios. For n, the numbering starts with 0 (for the control mixture), and then SZ2.5 – C2.5 and SZ5 – C5 are assigned with CM1 and CM2, respectively. The nine mixes are the following:

5. Table *An overview of the concrete mixes*

Mix designation	RR by CR [%]	RR by FR [%]	Cementitious mix
RC2 - F2 - CM0	20	20	Control (OPC)
RC2 - F2 - CM1	20	20	SZ2.5 – C2.5
RC2 - F2 - CM2	20	20	SZ5 – C5
RC3 - F1 - CM0	30	10	Control (OPC)
RC3 - F1 - CM1	30	10	SZ2.5 – C2.5
RC3 - F1 - CM2	30	10	SZ5 – C5
RC4 - F1 - CM0	40	10	Control (OPC)
RC4 - F1 - CM1	40	10	SZ2.5 – C2.5
RC4 - F1 - CM2	40	10	SZ5 – C5

2.2 Mixing process

The fresh concrete was mixed using a concrete pan mixer [10. Figure] with the following method: first, the coarse aggregates were mixed for 1 minute, then the fine aggregates were added, and the whole aggregate phase was mixed again for 1 minute. After the addition of half the required water content and a 30-second mixing came the cementitious mixture phase, when 30 seconds of mixing was also applied. Lastly, the rest of the required water content and the superplasticiser were added and mixed for 1 minute [6. Table].

10. Figure *Concrete pan mixer*

6. Table *The mixing method*

Stage name	Stage 1.	Stage 2.	Stage 3.	Stage 4.	Stage 5.
Materials mixed mixing time	Coarse aggregate mix 60 seconds	Fine aggregate mix 60 seconds	½ total water 30 seconds	Cementitious material mix 30 seconds	½ total water + SP 60 seconds

After mixing, the consistency of fresh concrete was tested on the flow table according to EN 12350-5 [55] [11. Figure]. If it did not satisfy the requirements of the F4 class, more SP was added, and the concrete was mixed for another minute. If the requirements were met, the concrete was vibrated into moulds using a vibro-table in two layers [12. Figure]. For compressive and flexural strength tests, two types of moulds were used: a cubic mould with dimensions of 150×150×150 mm and a prism mould used to produce 70×70×250 mm specimens for the flexural tensile strength [13. Figure].

11. Figure *Consistency measurement on the flow table*

12. Figure *Vibro-table*

13. Figure *Mould for a cube specimen (left) and prism specimens (right)*

After the tests were executed, the calculations were done in the MATLAB software to determine the compressive and flexural tensile strengths based on the collected information. The mean values for both mechanical properties were based on three specimens. For a graphical representation of the results, both MATLAB and Microsoft Excel software were used.

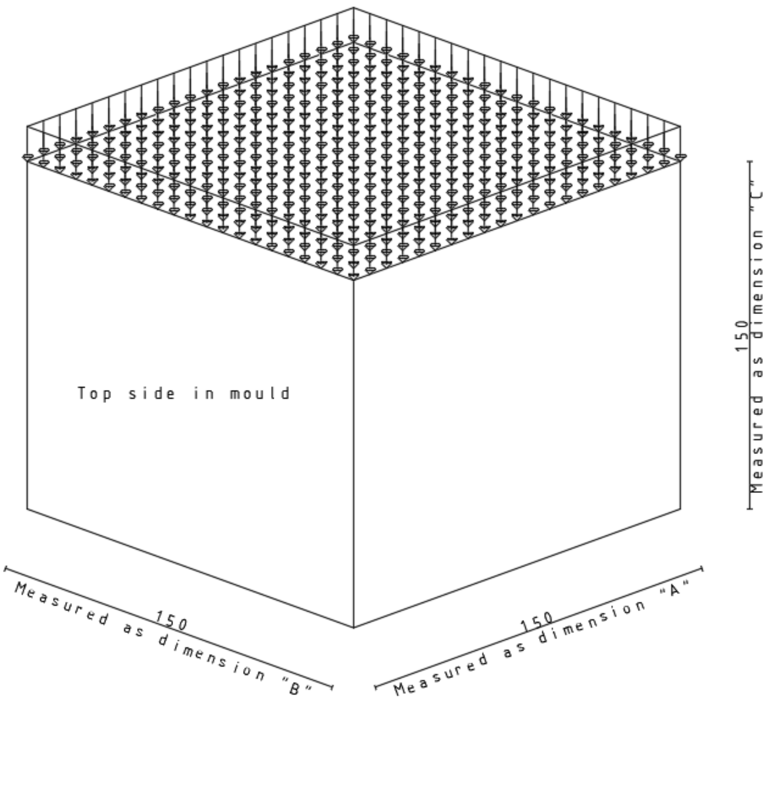
2.3 Flexural tensile- and compressive strength tests

Generally, 24 hours after casting, the specimens were demoulded, stored and tested according to the procedure prescribed by standard MSZ EN 12390-3 [56]. The samples were put underwater for 7 days, after which they were removed from the water and stored under laboratory conditions (20 °C, 50% RH) until 28 days of age. A total of 54 specimens were tested for both compressive and flexural tensile strength. The dimensions and mass of the hardened specimens were recorded for strength and density calculations.

2.3.1 Compressive strength test

Of each mix, three cubic specimens were used to investigate standard cube compressive strength. Compressive tests were executed with a 3000 kN hydraulic test [14. Figure]. During the test, force is distributed throughout the whole surface of the cube, as shown in [15. Figure]. The strength values and special failure modes were recorded for further analysis.

14. Figure *Compressive strength measurement on cubes*



15. Figure *Schematic representation of the compressive strength measurement, with average dimensions in millimetres (made with the AutoCAD software)*

The formula for compressive strength calculations [1. Equation] can be found in standard MSZ EN 12390-5:2009.

1. Equation

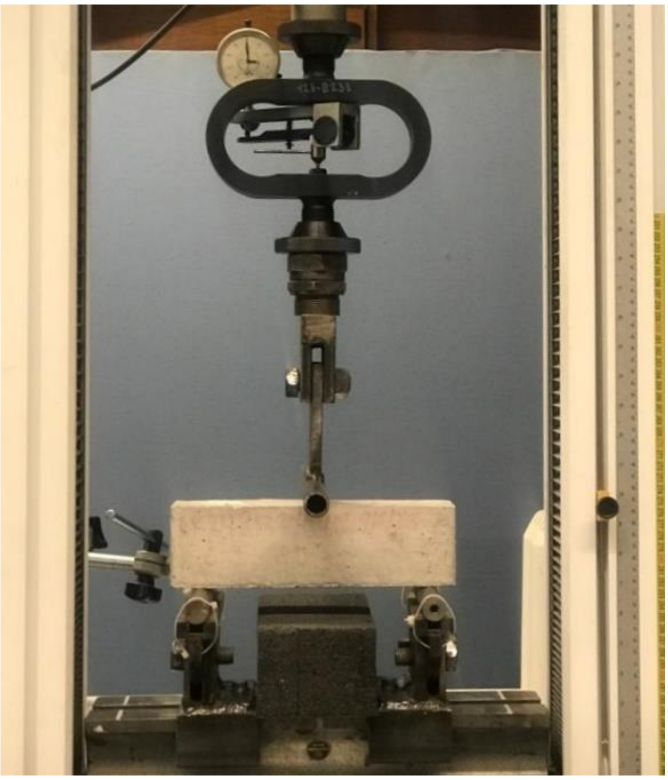
$$f_c = \frac{F_{max,c}}{a \cdot b} \ [N/mm^2]$$

Where:

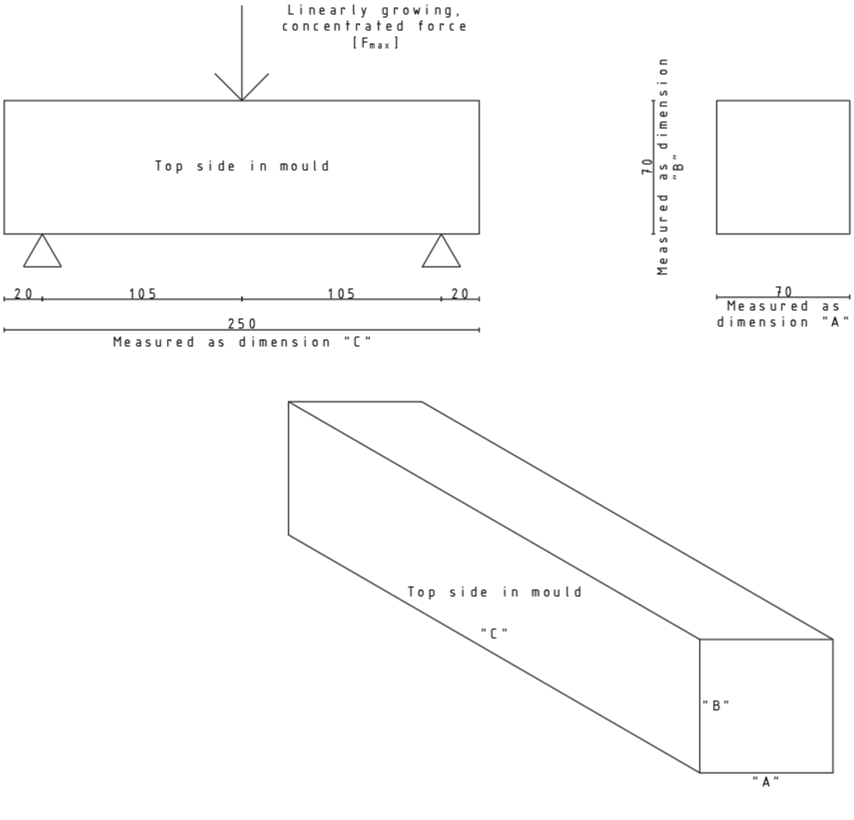
- f_c is the individual cube compressive strength measured in N/mm^2,
- $F_{max,c}$ is the individual maximum force measured in N,
- a and b are the dimensions of the cube in mm [15. Figure].

2.3.2 Flexural tensile strength test

For flexural tensile strength tests, the prisms were carefully placed into the machine so that the uneven surface of the original top side would not cause inaccuracies [16. Figure]. The prism is placed on two supporting axes spanning 210 millimetres; force is concentrated exactly 105 millimetres to the side of the supports. The machine is designed in a way that the three axes can tilt slightly during the test, providing consistent and linearly growing loading. The maximum force, cracking and failure modes were noted. The schematic representation of the test can be seen in [17. Figure].



16. Figure *Flexural tensile test on prisms*



17. Figure *Schematic representation of the flexural tensile strength measurement, with average dimensions in millimetres (made with the AutoCAD software)*

The formula for flexural tensile strength calculations is also found in standard MSZ EN 12390-5:2009 [57].

2. Equation

$$f_{fl} = \frac{3 \cdot F_{max,fl} \cdot c}{2 \cdot a \cdot b^2} \ [N/mm^2]$$

Where:

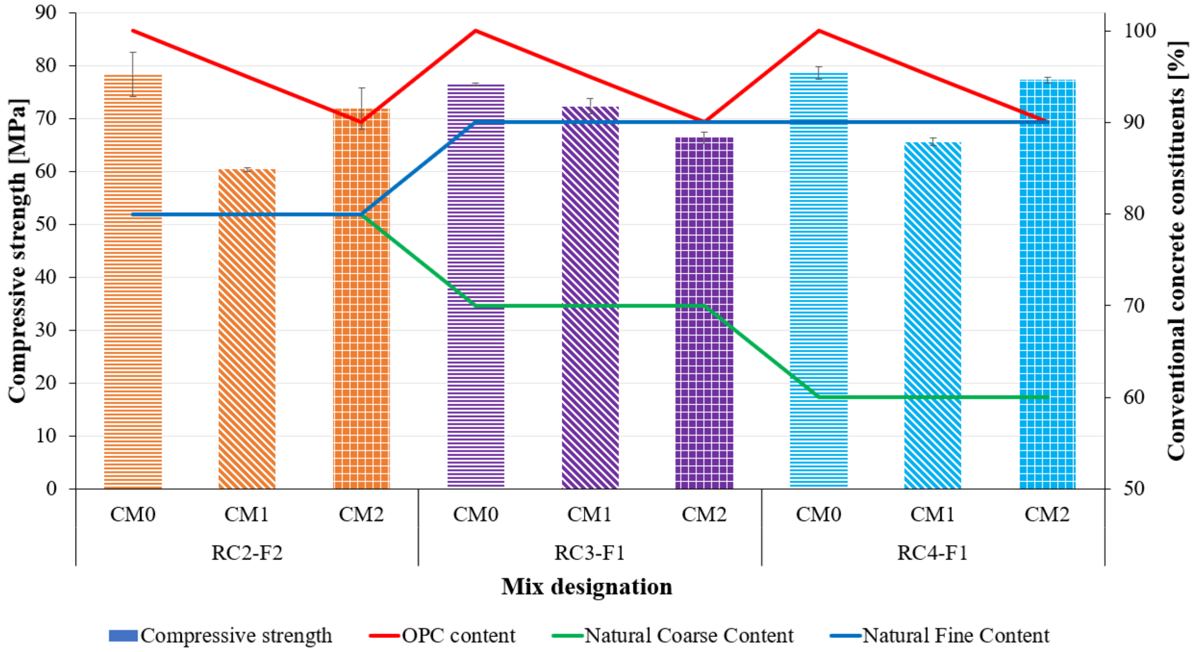
- f_{fl} is the individual flexural tensile strength measured in N/mm^2,
- $F_{max,fl}$ is the individual maximum force measured in *N*,
- *a*, *b* and *c* are the dimensions of the prism in *mm* [17. Figure].

3. Results and discussion

3.1 Compressive strength

The data obtained from the compressive strength tests can be seen in [18. Figure]. Data was analysed both on an individual and mix scale, where the average of three samples was taken for each mixture. Based on the compressive strength values, the research was successful in producing high-strength structural concrete, as even the lowest compressive strength was 60.33 MPa (RC2-F2-CM1).

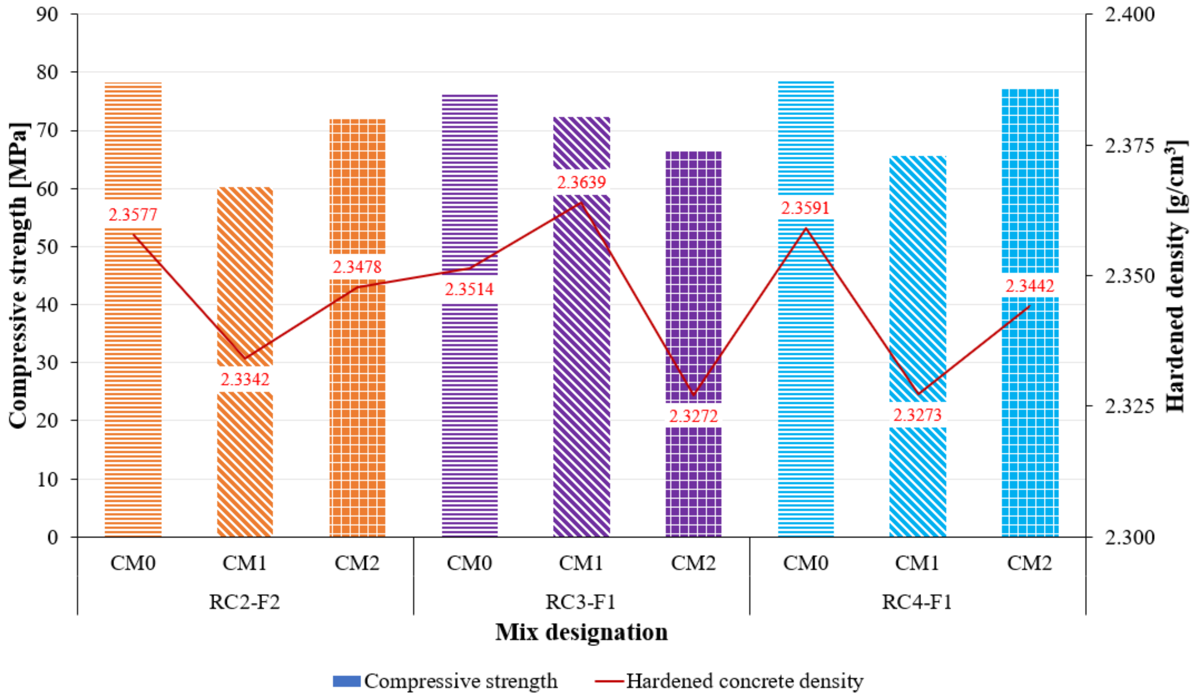
Control mixtures yielded compressive strength values within a narrow spectrum, with them being 78.32, 76.41 and 78.56 MPa for mixes RC2-F2-CM0, RC3-F1-CM0 and RC4-F1-CM0, respectively. The 2.15 MPa gap between the highest and lowest compressive strengths confirms the theory that if concrete mixes are designed based on the PD values of the aggregate phase, the mechanical properties will be similar despite the different RRs used.



18. Figure *The relationship between compressive strength values and conventional concrete constituents*

When blended cement pastes are considered, the trend between all nine mixes is less consistent. Apparently, RC2-F2 mixes and RC4-F1 mixes display a similar behaviour: with an inclusion of 5% WPP (CM1), the compressive strength decreases, but 10% WPP inclusion causes a significant increase compared to CM1. For better comparison to the control mixtures, the strength activity index (SAI) of mixes is a useful tool to evaluate results. The SAI of mix RC4-F1-CM2 (i.e., 0.98) is substantially higher than the SAI value of RC4-F1-CM1 (i.e., 0.83), showing a beneficial trend with the increase of WPP mix amount. The same trend is followed by concrete containing an aggregate mix of 20% CR and 20% FR. This phenomenon shows the importance of the PD [2. Table] values of the cementitious phase on concrete's mechanical properties. CM1 mix had a smaller PD and also a noticeably smaller compressive strength, meaning that in the case of these mixes, the cementitious PD is a valid concept and can be applied. Furthermore, the possible calcium phases retained in RCA based on virgin concrete could lead to earlier pozzolanic reactivity of WPPs. FR content is especially important in this regard. Due to its higher SSA and amount of cement phase contained because of the crushing process, its activity would possibly be higher. On the other hand, RC3-F1 concrete mixes showed distinctly different behaviour. In this case, CM1 had a higher compressive strength than CM2. Hence, for this group of concrete mixes, the cement hydration was leading in strength development with no substantial effect of either PD or pozzolanic reactivity.

However, hardened concrete density results [19. Figure] are mainly consistent with the trends recognised in the compressive strength behaviour of investigated mixes. This shows that although the hardened densities of RC2-F2-CM1 and RC2-F2-CM2, as well as RC4-F1-CM1 and RC4-F1-CM2, are directly proportional with their PDs, RC3-F1-CM1 and RC3-F1-CM2 behave differently, and their hardened densities are inversely proportional to the PDs of cementitious material mixes. The relationship between densities suggests that for compressive strength analysis, the PD of concrete mixes should also be evaluated when designing such mixes, as it might have a previously unanticipated influence. Therefore, this phenomenon should be further investigated in future research.



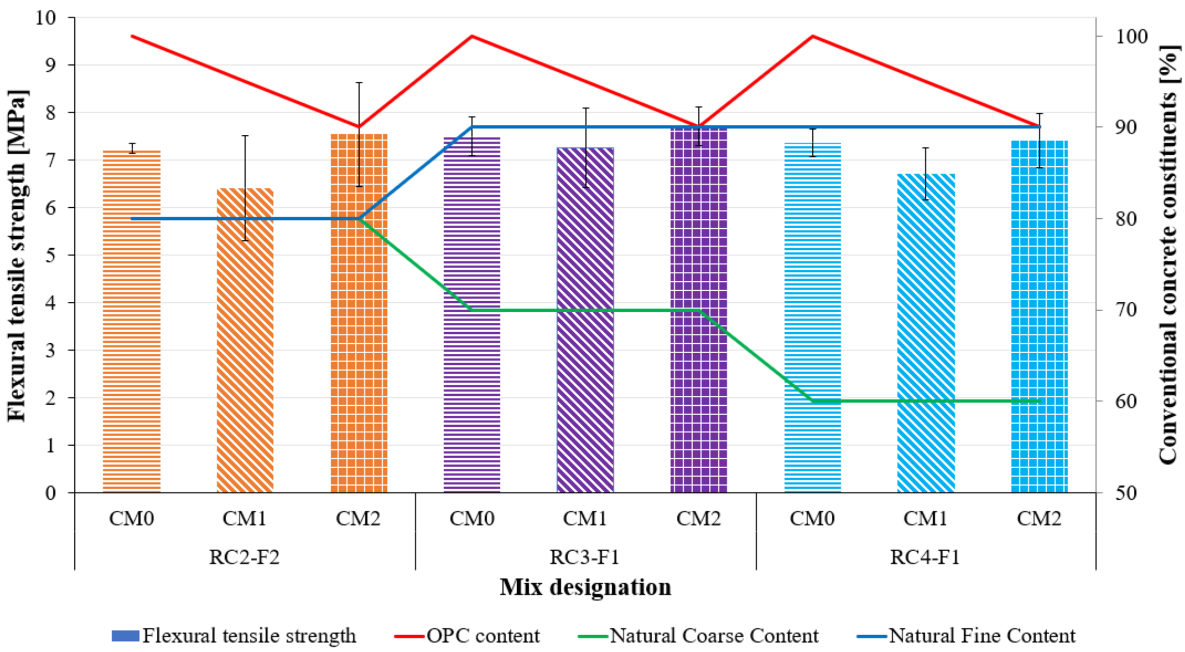
19. Figure *The relationship between compressive strength and hardened concrete densities*

3.2 Flexural tensile strength

The flexural tensile strength results of investigated concrete mixes are shown in [20. Figure]. In the case of control mixes (i.e., containing just OPC as cementitious material), the flexural tensile strength results were similar between different aggregate mixes, with values of 7.24, 7.5 and 7.37 MPa for mixes RC2-F2-CM0, RC3-F1-CM0 and RC4-F1-CM0, respectively. This observation justifies again the idea that mix design being optimised based on PD of aggregate phase can lead to similar mechanical properties irrespective of the RRs used. Overall, flexural tensile strength results for concrete mixes with different aggregate RRs showed an identical trend when cementitious material mixes differed, meaning that for the same aggregate mix, an increase in PD of cementitious paste led to advantageous results.

On the other hand, flexural tensile SAI also showed beneficial behaviour, where SAIs ranged from 0.89 to 1.04. Consequently, the experimental mixes displayed nearly the same, if not higher flexural tensile strengths than the control mixture, especially in the case of concrete made with CM2 cementitious mixes. For example, RC2-F2-CM2 had a SAI of 1.04, but RC3-F1-CM2 (SAI: 1.028) and RC4-F1-CM2 (SAI:1.005) also achieved higher strengths than their CM0 counterparts. Overall, the results show that the replacement of conventional concrete with alternative concrete mixtures made with RCA and WPPs as SCM can be done without repercussions, at least as far as flexural tensile strength is concerned.

According to the results, the flexural tensile strengths of the researched mixes follow the normal distribution, meaning that neither high nor low RCA content would be beneficial for flexural tensile strength. This knowledge could be further used for the flexural optimisation of recycled concrete mixes.



20. Figure *The relationship between flexural tensile strength and conventional concrete constituents*

3.3 Correlation between compressive- and flexural tensile strength

One of the main goals of this study was to assess the compressive- and flexural tensile strength of the investigated concrete mixtures in order to create a basic model that could be used both for further research as well as for sustainable concrete design and production. In this research, due to the limited amount of data and specimens, the developed model is not expected to be as comprehensive as needed, but it can serve as a milestone for further investigations on its applicability.

In general, based on up-to-date models developed for flexural tensile strength estimation, it is necessary to know compressive strength values. However, in alternative concrete mixes, the strength development is more complex and can be based on many parameters. As a first step of this study's model development, possible effects of aspects such as RCA or WPP content, PD, and hardened density are evaluated through regression for compressive strengths. To this end, a multiple linear regression was executed in the MATLAB software, which can be seen in [3. Equation]. From the developed equation, it can be concluded that all the variables identified have been influential in the compressive strength of the developed concretes. However, this model trend should be further investigated for larger dataset.

3. Equation

$$f_c = 173.24 \cdot WPS - 1090.98 \cdot PD + 2.85 \cdot CA - 2.95 \cdot FA + 126.74 \cdot \rho_{hardened} + 457.98$$

Where:

- f_c is the estimated individual compressive strength,
- WPS is the total RR of all WPPs $(0 < WPS < 1)$,
- PD is the packing density of the cementitious paste $(0 < PD < 1)$,
- CA is the total RR of CN by CR phases,
- FA is the total RR of FN by FR phases,
- $\rho_{hardened}$ is the expected density of hardened concrete.

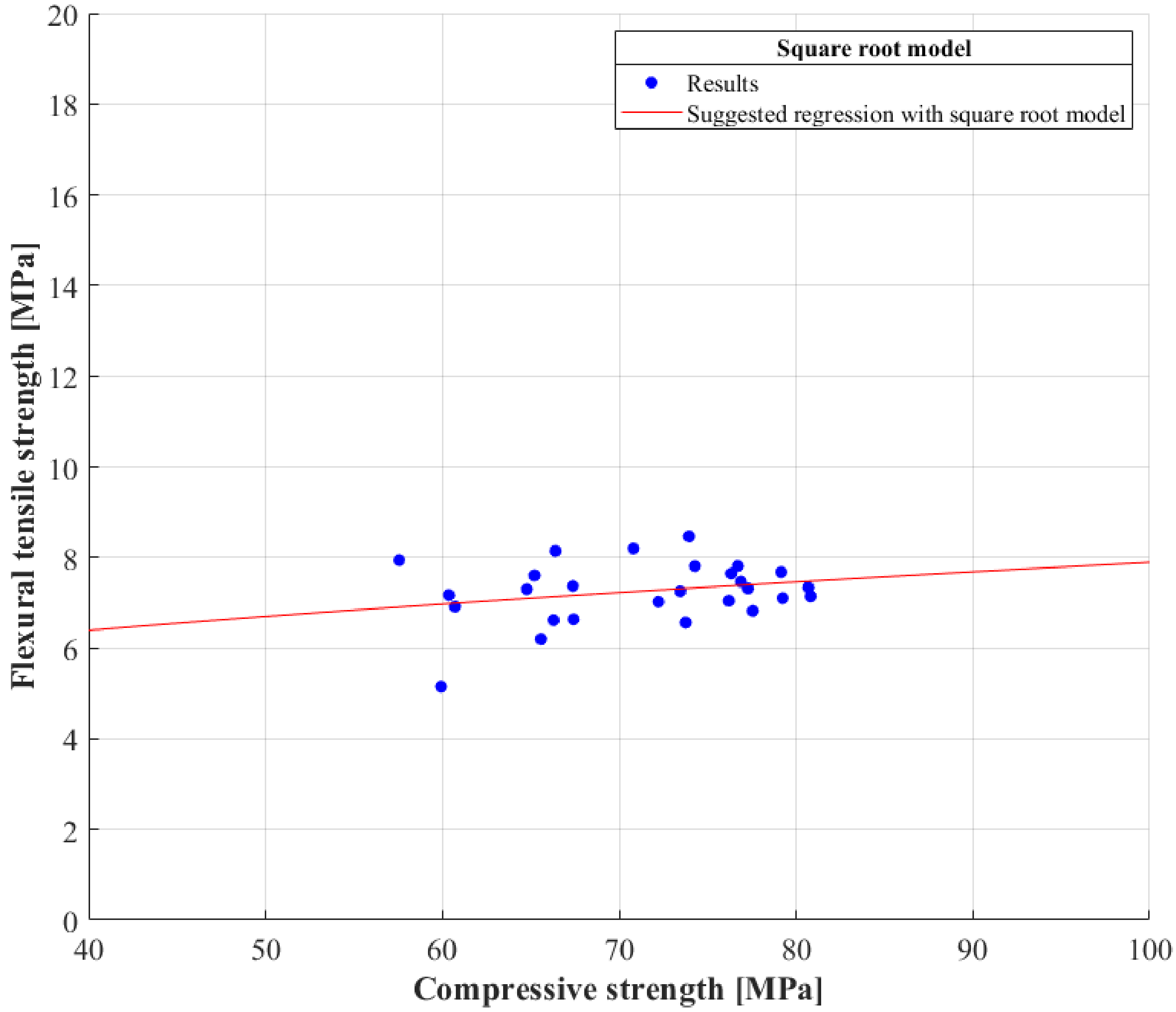
Based on the mechanical properties of investigated concretes and the regression model discussed above, two regression curves were produced in the MATLAB software. However, linear regression has been identified as inaccurate in this case. Also, based on previous research, it has been recognised that mostly square root regression and regression with a two-thirds power are used [1. Table]. The suggested square root model is described by [4. Equation] and is shown with the results in [21. Figure].

4. Equation

$$f_{fl} = 0.4081 \cdot \sqrt{f_c} + 3.812$$

Where:

- f_c is the individual compressive strength,
- f_{fl} is the individual flexural tensile strength.



21. Figure *Square root regression model for compressive - flexural tensile strength relationship*

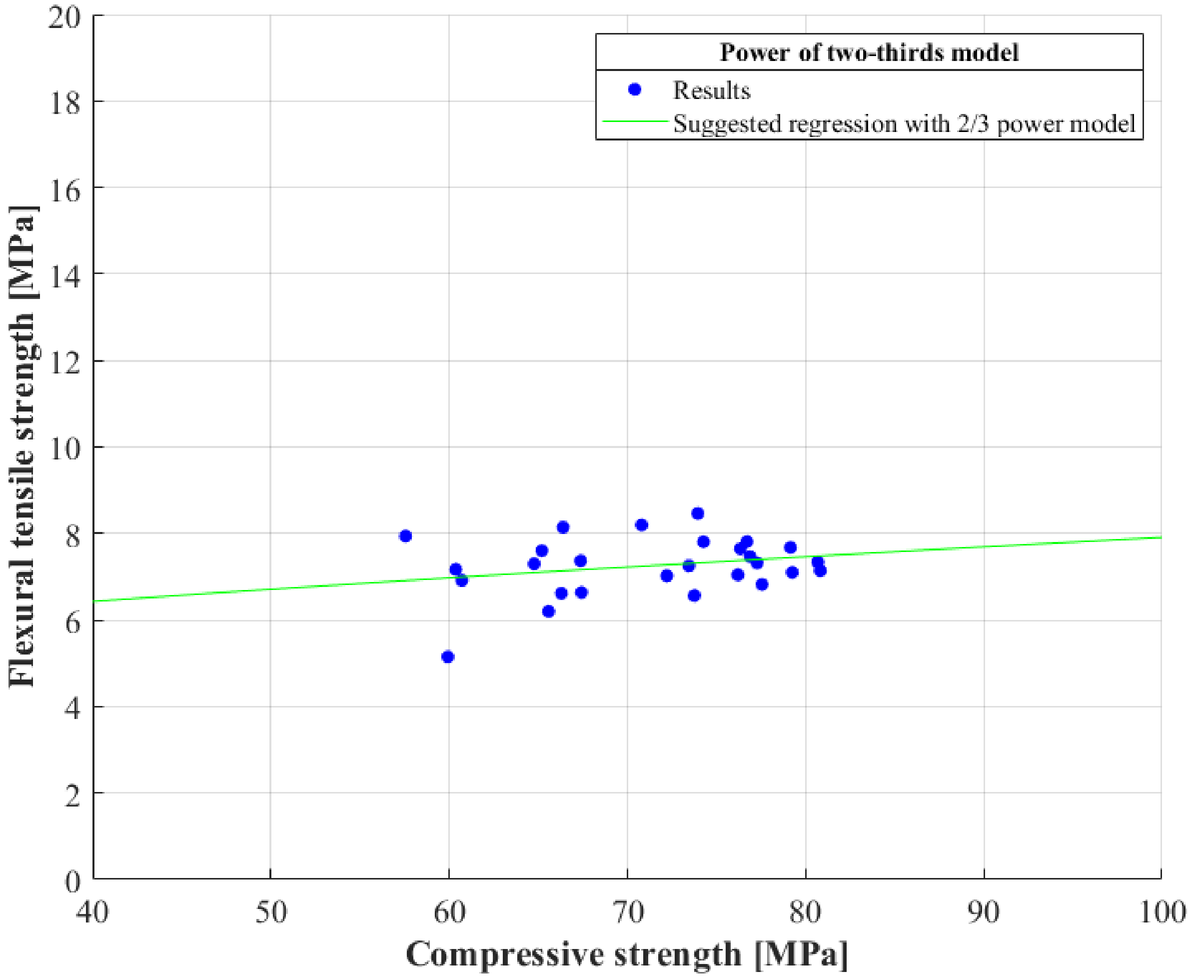
Another relatable model is a regression with a two-thirds power, which can be seen in [5. Equation] and is shown with research results in [22. Figure].

5. Equation

$$f_{fl} = 0.1506 \cdot \sqrt[3]{f_c{}^2} + 4.667$$

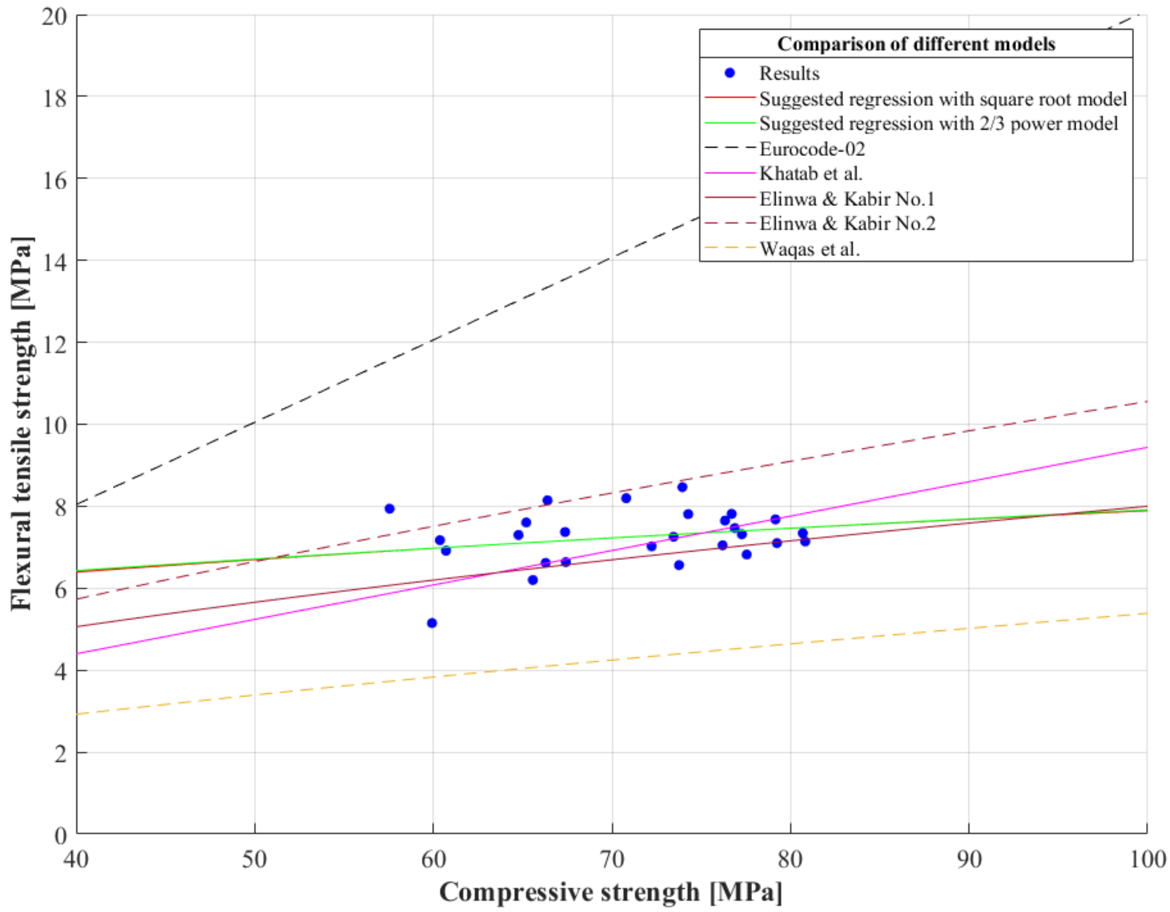
Where:

- f_c is the individual compressive strength,
- f_{fl} is the individual flexural tensile strength.



22. Figure *Two-thirds power regression model for the compressive - flexural tensile strength relationship*

The comparison of the suggested regression models and the models stipulated in standards and by other researchers can be seen in [23. Figure].



23. Figure *The compressive - flexural tensile strength relationship models* [1. Table]

As can be seen from [23. Figure], some models cannot be accurately applied to the results of this study. For example, the standard model from Eurocode-02 had to be discarded, which also affirms that linear models are not able to accurately predict the flexural tensile strength of the developed mixes. The models which were identified as possibly applicable to this study's mixes together with developed models in this study are presented in [7. Table].

7. Table *Comparison of the best fitting compressive - flexural tensile strength models (values were calculated using each concrete's average compressive strength from [19. Figure])*

Mixes and models	RC2-F2-CM0	RC2-F2-CM1	RC2-F2-CM2	RC3-F1-CM0	RC3-F1-CM1	RC3-F1-CM2	RC4-F1-CM0	RC4-F1-CM1	RC4-F1-CM2	Average
Developed square root regression	+2.54%	+8.92%	-3.56%	-1.6%	+0.28%	-7.39%	+0.81%	+6.11%	-0.13%	+0.66%
Developed power of two-thirds regression	+2.54%	+8.92%	-3.56%	-1.6%	+0.28%	-7.40%	+0.81%	+6.11%	-0.13%	+0.66%
Khatab et al.	+5.25%	-4.68%	-6.1%	-0.53%	-2.07%	-14.27%	+3.66%	-2.53%	+1.62%	-2,18%
Elinwa & Kabir, No.1	-2.21%	-3.12%	-10.08%	-6.8%	-6.34%	-15.56%	-3.8%	-3.43%	-5.13%	-6,27%
Elinwa & Kabir, No.2	+23.90%	+17.63%	+12.33%	+17.60%	+17.08%	+4.15%	+21.98%	+18.78%	+19.97%	+17,05%

According to [7. Table], there is no significant difference between the power of two-thirds model and the square root regression model in predicting flexural tensile strengths. It can also be observed that the model developed by Khatab et al. can be applied with minimal inaccuracy and underestimation, in this case -2.18%. The minor difference between the model of Khatab et al. and the model established in this research is worthy of attention since it proves that RAC mixes display similar mechanical characteristics regardless of the type and quantity of the cementitious mix used. Both models of Elinwa & Kabir show larger differences: the first model of the researchers underestimates the flexural tensile strengths of the mixes produced, whereas the second model is a high overestimation. The models confirm that the prediction of flexural tensile strength in the case of RAC made with WPP SCMs should be done with at least square root models instead of the regular linear regression approach.

4. Conclusions

The main goal of this study was to investigate the mechanical properties of sustainable concretes made with recycled concrete aggregate (RCA) and waste perlite powders (WPPs) as supplementary cementitious materials (SCMs) using the packing density model. The following conclusions can be made based on the experimental investigation:

- The compressive strength values of the developed mixes prove that high-strength structural concrete can be produced with RCA and WPP as SCMs, with values ranging between 60.33 MPa and 78.56 MPa.
- Compressive strength values of control mixtures (those made without SCM addition) were very similar, thus confirming the theory that if concrete mixes are designed based on the packing density (PD) values of the aggregate phase, the mechanical properties will be similar, even if different replacement ratios (RRs) are utilised.
- If the effects of blended cement pastes are considered, the results are less consistent. At 5% WPP inclusion, most mixes demonstrated a smaller compressive strength compared to those made with 10% WPP RR. An exception to this was the group made with 30% coarse recycled aggregate (CR) and 10% fine recycled aggregate (FR). In the case of such mixtures, the mixes made with 5% WPP were stronger than those made with 10%.
- Hardened concrete density results were more consistent with the trend observed in concretes made with 30% CR and 10% FR, suggesting that for mix design, the PD of hardened concrete should also be investigated.
- In terms of flexural tensile strength, the developed mixes were equally capable as the control mixes, with some values even surpassing them. The flexural tensile properties of the control mixes were very similar, again proving the validity of considering aggregate phase PDs by concrete design.
- Research models and models codified in standards were compared with the test results. The comparison showed that linear models, such as the model presented in Eurocode-02, are not applicable in the case of the concrete mixes produced in the research. Instead, square root and two-thirds power regression models should be used. Of the research models, those developed by Khatab et al. and Elinwa & Kabir can be utilised with adequate accuracy.
- Based on the research data, approximate regression models were developed. For compressive strength prediction, factors such as WPP, CR and FR content, cementitious PD and density were considered. For flexural tensile strength estimation, a square root- and a two-thirds power regression model were created.

Overall, the alternative concrete mixes and models developed and investigated in this study are viable to produce environmentally friendly, sustainable and economically beneficial concretes without adversely affecting mechanical behaviour. Further research concerning concrete packing density and its effects on mechanical properties, as well as durability should be conducted. Future research should also opt to use more specimens for a larger dataset in order to validate the developed prediction models.

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