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Optimisation of cement-sand mortar compositions modified with fine-grained rubber powder in relation to their mechanical performance

Abstract: The article presents the results of a research study aimed at determining the optimum amount of 0/1 mm rubber powder additive for cement-sand mortars (CSM) used in asphalt-cement concretes (ACC), to meet the requirements for mineral-cement-emulsion mixtures (MCEM) due to the lack of regulations concerning these concretes. The study includes test results for indirect tensile strength (ITS) and stiffness modulus (IT-CY method) at 5°C, performed after 7 and 28 days of curing. The regression curves for *ITS* and *IT-CY* values in relation to rubber powder content after 7 days were well described by exponential functions, whereas the results after 28 days were best fitted by linear functions. It has been observed that compliance with ITS limit requirements excludes CSR mortars that meet IT-CY requirements, and vice versa. In order to clearly define the requirements for mortar mixtures, minimum and maximum *ITS* and *IT-CY* values were proposed so that the samples would meet both requirements simultaneously. Supplementary tests were also carried out to assess water resistance.

Keywords: cement-sand mortars, recycling, rubber powder.

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1. INTRODUCTION

The article presents the results of an experimental study aimed at determining the optimum amount of 0/1 mm rubber used in asphalt-cement concretes (ACC), in order to meet the requirements for mineral-cement-emulsion mixtures (MCEM) determined in [1]. The analysed material consists of waste (rubber recovered from used tyres) and highly CO_2-emitting material (cement). The cement industry is classified as the second-largest emitter of carbon dioxide (CO_2) worldwide, accounting for approximately 5% of global greenhouse gas emissions [2], and the third-largest emitter of air pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), and sulphur dioxide (SO_2) [3]. Approximately 900 kg of CO_2 is released in the production of one tonne of cement, representing about 8% of the emissions from an average concrete mixture [4]. Around 60% of CO_2 emissions during cement production originate from the chemical decomposition of limestone ($CaCO_3$), while approximately 30-35% result from fuel combustion in the cement kiln [5]. The decarbonization of the cement industry is therefore one of the key components of global economic reform.

Industrial waste and end-of-life plastics also constitute significant sources of environmental pollution. A particularly important contributor is the automotive industry, which generates large volumes of waste in the form of used tyres. The stockpiling of end-of-life tyres poses not only an environmental burden but also a fire hazard due to their potential for self-ignition.

The high CO_2 emissions associated with cement and concrete production can be mitigated through the use of various supplementary materials. Numerous studies have demonstrated that some of these additives enable a substantial reduction in greenhouse gas emissions, contributing to the development of so-called “green concrete”. One such material, suitable for use as an aggregate substitute in structural concrete, is crumb rubber derived from processed rubber waste or end-of-life tyres.

Rubber granulate can be produced using cryogenic, mechanical, mechanochemical, or chemical methods. The cryogenic process involves freezing the rubber with liquid nitrogen followed by grinding, which yields granules with smooth surfaces. The mechanical method consists of shredding the rubber in processing installations equipped with cracker mills, separators (fabric, magnetic, steel), and vibrating screens [6]. In the mechanochemical method, polymers within processed tyres are not fully decomposed, thus retaining their elastic properties. By contrast, chemical treatment induces irreversible changes in the elastomeric matrix of the tyre material [7].

In the United States, according to data from the U.S. Tire Manufacturers Association (USTMA), approximately 79% of end-of-life tyres in 2023 were repurposed through recycling, energy recovery, retreading, or asphalt production [8]. According to the USEPA [9], about half of the tyres processed are incinerated for energy recovery. In Europe, the European Tyre and Rubber Manufacturers’ Association (ETRMA) reported that in 2019 about 94% of used tyres were collected and processed, of which approximately 54-62% were directed to material recycling and about 33-40 % to energy recovery [10].

2. APPLICATION OF CRUMB RUBBER IN CONCRETES AND MORTARS

Crumb rubber has been increasingly applied in the production of cement- and asphalt-based composites. It has been utilised, among others, in the manufacturing of paving slabs [11], structural concretes with compressive strengths in the range of 20-32 MPa [12, 13], columns [14], as well as mineral-asphalt mixtures for road pavements [15].

Studies on the composition of concrete mixtures modified with crumb rubber have been the subject of numerous research works [16]. In [17], it was found that the production of concretes containing crumb rubber requires a higher water content compared to conventional concrete. Reducing the water content to a water-to-cement *w/c* ratio below 0.50 decreases the workability of fresh crumb rubber concrete. Therefore, as the rubber content increases, the *w/c* ratio should also be increased. Moreover, water absorption by crumb rubber concrete may shorten the setting time and reduce the overall strength [18].

The use of rubber as a coarse aggregate replacement reduces the stiffness, durability, hardness, and density of concrete [19, 20]. According to several studies [21, 22, 23], replacing 5-30% of aggregate with crumb rubber can result in poor compaction, high porosity, low workability, and reduced strength. A more favourable solution is the use of crumb rubber in the form of fibres, in amounts ranging from 5-20%, which may improve stability, workability, and durability [24].

In [25, 26], it was reported that the compressive strength of concrete incorporating silica fume or fly ash either remained unchanged or increased relative to unmodified samples, depending on the content of crumb rubber used as an aggregate replacement up to 15% by volume. Other studies demonstrated a reduction in compressive strength when the crumb rubber content exceeded 3.5% after 28 days of curing [22, 23, 27]. Further investigations confirmed that compressive strength decreased when more than 10% of aggregate was replaced with crumb rubber [18, 20, 28]. It was shown that compressive strength may be reduced by approximately 20-50%, depending on the mixture composition. Similar conclusions were drawn in additional studies [29, 30, 31], confirming that an increase in crumb rubber content results in a decrease in compressive strength at both 14 and 28 days of curing.

The tensile strength of concrete modified with crumb rubber has been found to be lower than that of control specimens, with reported reductions ranging from 10% [29] to 36.4% [32].

Subsequent studies demonstrated that replacing both fine and coarse aggregates with crumb rubber may reduce the modulus of elasticity by up to approximately 81% [33, 34]. In another study [35], it was shown that substituting aggregate with 0/4 mm rubber powder at levels of 20% and 30% resulted in compressive strength reductions of about 50% and 80%, respectively.

The obtained stress-strain curves indicated that the sharp peak observed in control mortars was replaced by a quasi-plateau in rubber-modified mortars. As long as this plateau phase persists, it can be assumed that the coalescence of microcracks has not yet been completed. This phenomenon can be explained by the presence of rubber particles, which inhibit the formation of cracks. On the one hand, rubber grains may be considered relatively weak; however, when microcracks reach the rubber-cement interface, the stress concentration at their edges decreases. On the other hand, compared to voids, rubber particles have a higher energy absorption capacity, which contributes to limiting further crack propagation.

The study also demonstrated the benefits of combining fibre reinforcement with the addition of rubber granulate, enabling the production of concrete with enhanced crack resistance.

In [36], water absorption tests were conducted on a cement mortar in which 30% of the sand was replaced with crumb rubber. It was shown that the rubberised mortar exhibited a water absorption of approximately 32%, about four times greater than the reference mortar. At the same time, the density of the rubberised mortar was 40% lower than that of the reference sample. SEM micrographs of mortar surfaces demonstrated that the microstructure of cement mortar with rubber is more complex to interpret than that of conventional mortar, with sand grains easily distinguishable from rubber particles. The authors concluded that the reductions in compressive and flexural strength in rubberised mortar were more closely related to the increased porosity than to weak interfacial adhesion. They hypothesised that rubber particles act as air-entraining agents during the mixing of cement mortars. Based on porosity measurements, it was determined that porosity is proportional to rubber content, with the rubber-to-void ratio estimated at 0.93-0.95. Furthermore, the reference mortar exhibited compressive and flexural strengths approximately 12 times and 4 times higher, respectively, than those of the rubberised mortar.

In [37], tests were performed on concrete with a compressive strength of 30 MPa, Portland cement, a *w/c* ratio of 0.45, and a plasticiser. After replacing 25% and 37.5% of sand with fine rubber granulate, compressive strengths of 1.2 MPa and 0.8 MPa were obtained, respectively. When both coarse and fine rubber aggregates were used, the resulting strength was about 1.2 MPa. It was found that rubberised concrete has a higher air content than conventional concrete. This effect is attributed to the non-polar nature and hydrophobic properties of rubber particles, which promote air retention. This conclusion was supported by density measurements: conventional cement mortar exhibited a density of 2.49 g/cm^3 compared with 1.8 g/cm^3 for rubberised mortar, regardless of aggregate size.

The mechanical properties of cement mortars and cement-asphalt mortars containing rubber powder were described in [38]. Tests on a cement-rubber-emulsion mortar with proportions CEM : RP : AEm = 2 : 1 : 1 yielded an indirect tensile strength of *ITS* = 1.6 MPa and a stiffness modulus of *IT-CY* = 1500 MPa, satisfying the technical requirements for cement-emulsion mixtures (CEM) [1]. The addition of rubber powder alone or asphalt emulsion alone reduced the stiffness modulus by approximately four times compared with pure cement mortar.

In [39], experimental bending tests were performed on beams made from cement mortars and cement-asphalt mortars containing rubber powder with a particle size up to 0.1 mm. Four- point bending tests were carried out at 5°C, 23°C, and 50°C after 28 days of curing. The deformation process was monitored until failure using a Digital Image Correlation (ARAMIS) system. The largest deformations were recorded in mortars with the highest rubber powder content. It was shown that the deformability of rubber-modified mortars increased by a factor of 2-3 compared with cement mortar, while their flexural strength decreased by 30%.

The reduction in compressive strength of mortars and concretes containing rubber is primarily caused by poor adhesion at the rubber-cement paste interface during hydration. Surface modification of rubber can improve adhesion, hydration, and mechanical strength. Positive results were obtained through NaOH treatment [40], which reduced porosity and increased strength. Similarly, the use of tannic acid (TA) and calcium carbonate ($CaCO_3$, particle size < 5 μm) improved rubber hydrophilicity and enhanced bonding with cement mortar [41]. Another study [42] demonstrated that partial oxidation of rubber particles leads to improved strength in rubberised concrete [43]. Improvements in interfacial bonding between rubber and aggregates were also observed with the use of silanes, as confirmed by scanning electron microscopy [44]. Furthermore, the addition of 0.5% and 1% nanosilica to rubber mortars increased compressive strength and reduced the rate of stiffness modulus reduction during drying shrinkage [45].

3. INVESTIGATION OF MORTARS MODIFIED WITH RUBBER POWDER

3.1. MATERIALS

For the preparation of mortars, a multi-component Portland cement CEM I 42.5 R was used. Rubber powder with a particle size of 0/1 mm was obtained by mechanical grinding and was supplied by one of the professional manufacturers. Natural sand was employed as the fine aggregate. The particle size distribution of the materials incorporated as inclusions within the cement matrix is presented in Table 1.

Table 1. Particle size distribution [% (m/m)]

Sieve # [mm]	Sand 0/2 mm	Rubber powder 0/1 mm
2	1.6	–
1	–	15.2
0.5	41.6	47.5
0.125	55.3	36.4
0.063	1.2	0.0
< 0.063	0.3	1.0

3.2. MORTAR COMPOSITIONS

For the experimental programme, 12 specimens of each cement-sand-rubber (CSR) mortar composition were prepared. Tests were carried out after 7 and 28 days of curing. Compaction of specimens was performed manually to achieve maximum mould filling.

The water content was determined experimentally based on the water-to-cement ratio: $w/c = 0.52$ for mixtures A, B, C; $w/c = 0.50$ for mixtures D, E, F; and $w/c = 0.49$ for mixtures G, H, I (Table 2). Curing of the specimens was ensured by protecting them from drying through storage in sealed plastic bags for the duration of the curing period.

Table 2. Compositions of CSR mortars [% (m/m)]

Composition	Water [%]	Cement [%]	Rubber powder [%]	Sand [%]
A	13	25	15	47
B	13	25	20	42
C	13	25	25	38
D	15	30	15	40
E	15	30	20	35
F	15	30	25	30
G	17	35	15	33
H	17	35	20	28
I	17	35	25	23

3.3. MECHANICAL PROPERTY TESTING

3.3.1. Indirect tensile strength *ITS* after 7 and 28 days

Tests of indirect tensile strength ITS were carried out in accordance with PN-EN 12697-23:2003, and stiffness modulus tests were conducted using the IT-CY method according to PN-EN 12697-26, at a test temperature of 5°C. The evaluation of the obtained results was performed with reference to the requirements [1] for traffic load category TC3-4. Prior to testing, the specimens were conditioned for a minimum of 4 hours in a climate chamber (Fig. 1).

Fig. 1. Conditioning of cylindrical CSR mortar specimens

The indirect tensile strength tests were conducted using a compression testing machine with piston speed 50 mm/min (Fig. 2). For the analyzed mixtures with rubber, we do not expect the loading rate to influence the obtained results, although the properties of rubber (in this case, rubber powder) are significantly temperature-dependent. Rather, we anticipate elastic behaviour (close to linear-elastic) within the strain range limited by the expected micro- and macro- damage. The *ITS* parameter was calculated according to the eq. (1):

$$ITS = \frac{2 \cdot P}{\pi \cdot D \cdot h}, \tag{1}$$

where:

P – maximum compressive load [N],

D – specimen diameter, rounded to 0.1 mm,

h – specimen thickness/height, rounded to 0.1 mm.

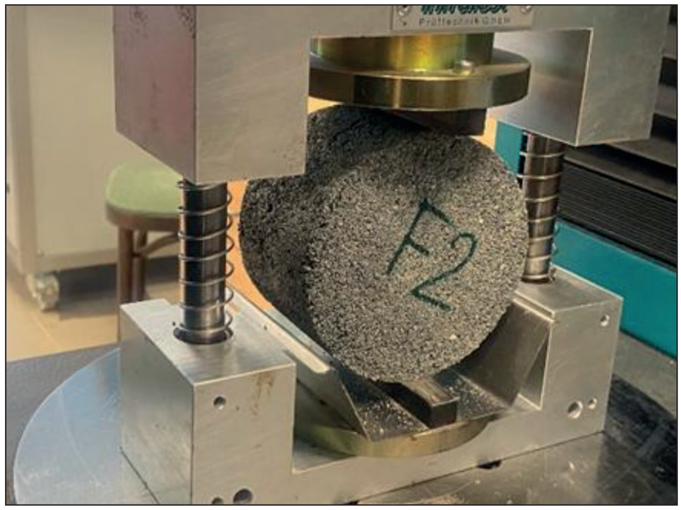

Fig. 2. ITS testing of cylindrical CSR mortar specimen

The results of the indirect tensile strength *ITS* tests are presented in Table 3 and Figs 3-4. The requirement after 7 days of curing is specified as 0.5 MPa < *ITS* < 1.0 MPa. At this stage, mixtures A, B, D, E, H, and I met the requirements. Subsequently, tests were conducted on selected mortars after 28 days of curing. Experimentally, in order to verify the results, mortar F was tested after 28 days, despite not meeting the requirements for 7 days, and mortar H, which would certainly meet the 28-day requirements, was discarded. At this stage, the requirements are defined as 0.7 MPa < *ITS* < 1.6 MPa. These criteria were fulfilled by mortars A, B, D, E, and I.

The coefficients of variation of the obtained results, depending on the composition, ranged from 1% to 28%.

Table 3. Indirect tensile strength *ITS* after 7 and 28 days with statistical parameters

Composition	ITS^7 [MPa]	Standard deviation	Coefficient of variation C.V. [%]	ITS^{28} [MPa]	Standard deviation	Coefficient of variation C.V. [%]
A	0.88	0.11	12	0.93	0.04	4
B	0.60	0.07	11	0.64	0.10	15
C	0.40	0.01	1	–	–	–
D	0.95	0.14	15	1.15	0.04	4
E	0.39	0.05	12	0.85	0.24	28
F	0.27	0.02	9	0.54	0.09	17
G	1.28	0.09	7	–	–	–
H	0.90	0.03	3	–	–	–
I	0.67	0.11	17	0.86	0.07	8

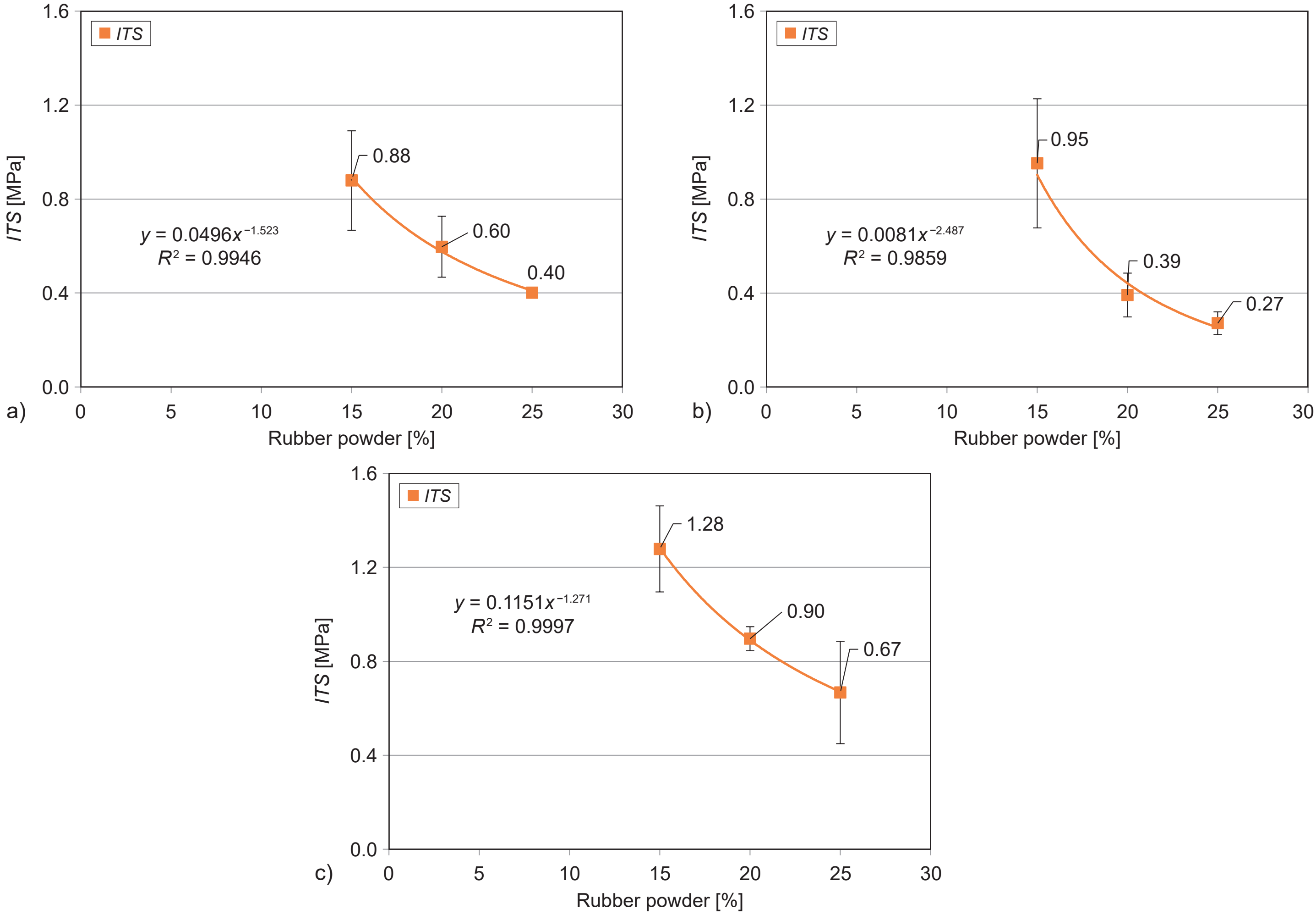

Fig. 3. Indirect tensile strength *ITS* of cylindrical CSR mortar specimens with: a) CEM = 25%, b) CEM = 30%, c) CEM = 35%, after 7 days

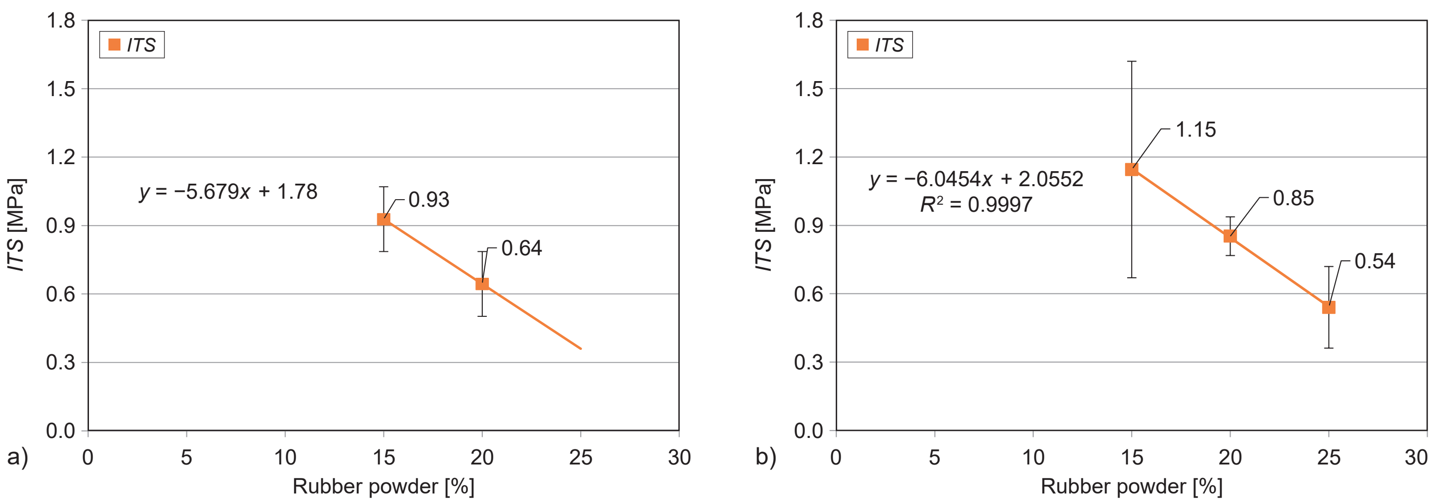

Fig. 4. Indirect tensile strength *ITS* of cylindrical CSR mortar specimens with: a) CEM = 25%, b) CEM = 30%, after 28 days

3.3.2. Stiffness modulus *IT-CY* after 7 and 28 days

The stiffness modulus IT-CY test was also carried out in the indirect tensile configuration (Fig. 5). The load was applied perpendicular to the cylinder axis to generate a defined displacement recorded by sensors positioned orthogonally to the load direction. The tests were carried out under the following conditions: deformation increase time 124 ± 4 ms, target deformation level 5 μm, time between load cycles 3 s, number of test pulses 10, number of measurement pulses 5, and Poisson's ratio assumed as 0.3.

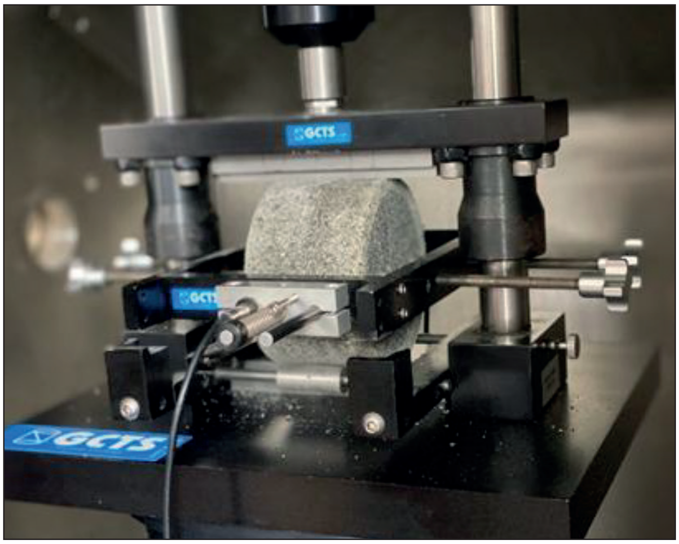

Fig. 5. *IT-CY* stiffness modulus test setup

The stiffness modulus E_S was determined according to the eq. (2):

$$E_S = \frac{L \cdot (\nu + 0.27)}{D \cdot t}, \tag{2}$$

where:

L – maximum (absolute) value of the load applied to the specimen [N],

ν – Poisson's ratio (may depend on temperature),

D – maximum horizontal deformation of the specimen, measured on the lateral surface of the cylinder in a plane perpendicular to the load direction and passing through the specimen axis [mm],

t – specimen thickness/height [mm].

The results of the *IT-CY* stiffness modulus tests are presented in Table 4 and Figs 6-7. The requirement after 7 days of curing was specified as 1,500 MPa < *IT-CY* < 4,500 MPa. At this stage, mixtures C, E, F, and I met the requirements. Experimentally, in order to verify the results despite not meeting the requirements, mortars A and B were tested, and mortar C was discarded because it did not meet the ITS requirements. Mortar D was tested after 28 days to verify the results after 7 days, while mortar H, which would certainly meet the 28-day requirements, was discarded. After 28 days of curing, mortars A, B, E, F, and I fulfilled the requirement defined as 2,000 MPa < *IT-CY* < 7,000 MPa.

The coefficients of variation, depending on the mortar composition, ranged from 6% to 18%.

Table 4. *IT-CY* stiffness modulus after 7 and 28 days with statistical parameters

Composition	*IT-CY*^{7} [MPa]	Standard deviation	Coefficient of variation C.V. [%]	*IT-CY*^{28} [MPa]	Standard deviation	Coefficient of variation C.V. [%]
A	9,071	822	9	6,162	398	6
B	4,922	340	7	4,788	484	10
C	2,783	181	7	–	–	–
D	9,124	587	6	9,524	657	7
E	4,048	401	10	6,541	1,167	18
F	2,350	224	10	3,612	267	7
G	8,433	448	5	–	–	–
H	6,013	328	5	–	–	–
I	4,169	616	15	4,778	447	9

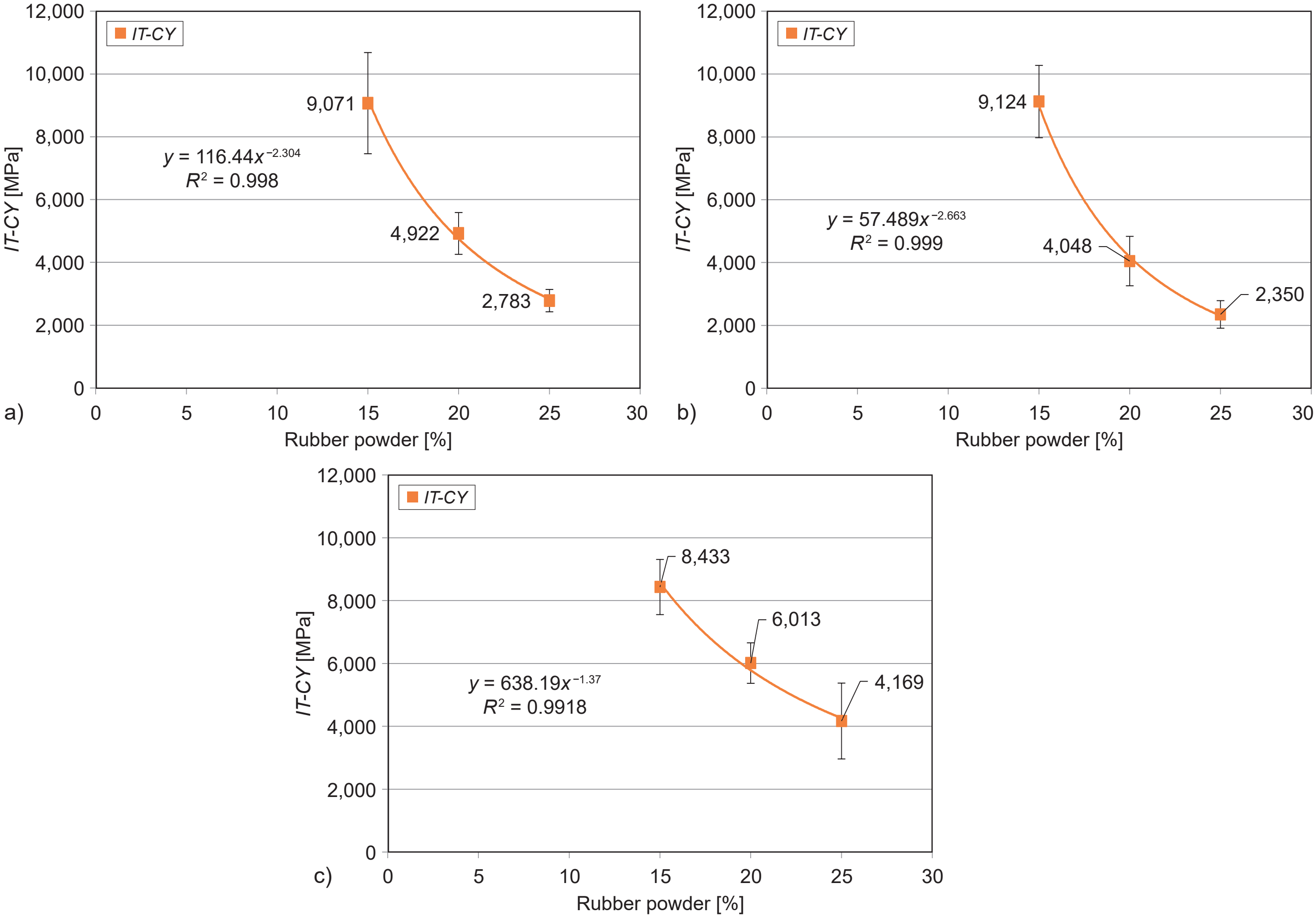

Fig. 6. *IT-CY* stiffness modulus of cylindrical CSR mortar specimens with: a) CEM = 25%, b) CEM = 30%, c) CEM = 35%, after 7 days

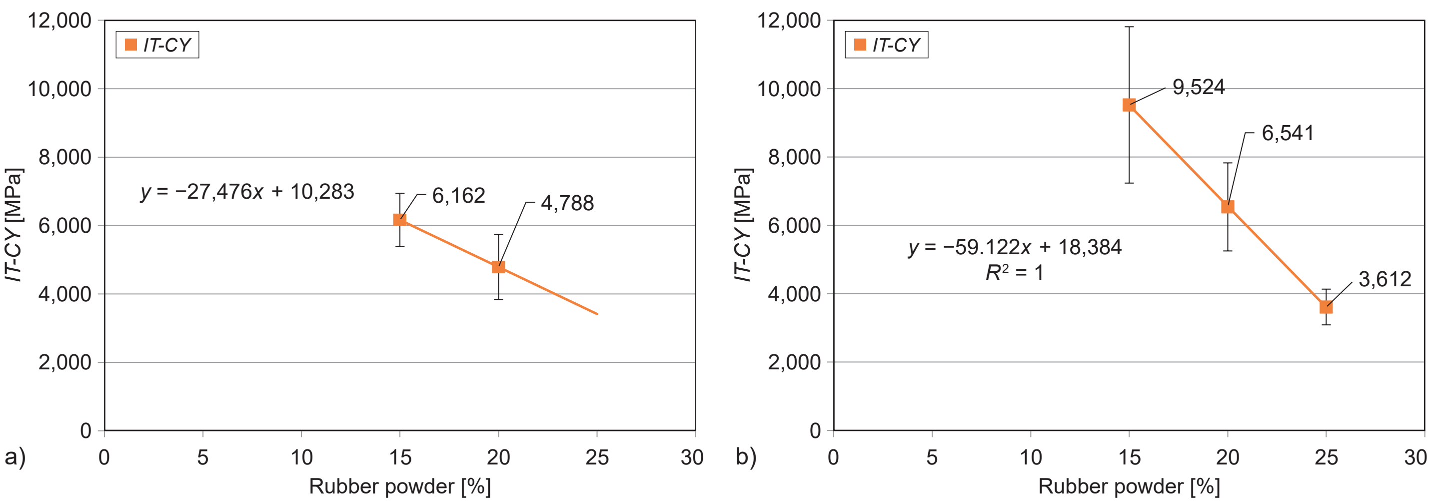

Fig. 7. *IT-CY* stiffness modulus of cylindrical CSR mortar specimens with: a) CEM = 25%, b) CEM = 30%, after 28 days

3.3.3. Water resistance

The water resistance test, i.e., the residual indirect tensile strength after water storage, was performed in accordance with the technical recommendations [1]. The procedure involved dividing the specimens into two groups after 14 days. One group was stored in air at +20 ± 5°C for an additional 14 days, while the other group was placed in a water bath at the same temperature, fully submerged, for 14 days.

After 28 days, both the air-stored and water-conditioned specimens were prepared for indirect tensile strength and stiffness modulus testing at +5°C. The water resistance index was calculated as the ratio of the indirect tensile strength of water-conditioned specimens to that of dry specimens *ITSR*. In the experimental water resistance tests, an analogous ratio was also calculated for the stiffness modulus of wet to dry specimens *IT-CYR*.

The results for six specimens of two selected mixtures rubber powder 20% and CEM = 25% (B), and rubber powder 25%, CEM = 35% (I) are presented in Table 5.

Table 5. Water resistance *ITSR* and *IT-CYR* of mortar compositions

Mortar composition	Dry specimens		Wet specimens		*ITSR*	*IT-CYR*
	ITS [MPa]	*IT-CY* [MPa]	*ITS* [MPa]	*IT-CY* [MPa]		
B	0.64	4788	0.72	6022	1.1	1.3
I	0.86	4778	0.99	7333	1.1	1.5

The tested mortars satisfied the requirements for residual indirect tensile strength after water storage, specified as *ITSR* > 0.8 for medium traffic load categories TC3 and TC4. Both mortars achieved values of approximately 1.1. When resistance was assessed based on *IT-CYR*, higher values were obtained compared with *ITSR*, with CSR mortar I showing higher results than CSR mortar B (1.5 vs. 1.3, respectively). The higher values of the *ITS* and *IT-CY* test results for mortar samples B and I after soaking in water, compared to dry samples, may be the result of their "curing", which is recommended for hydraulically bound mixtures. Another explanation may be incomplete cement hydration in the case of dry samples.

4. CONCLUSIONS

The results of the indirect tensile strength *ITS* and stiffness modulus *IT-CY* tests indicate that, regardless of cement content, increasing the proportion of rubber powder at the expense of sand reduces both parameters. The regression curves of *ITS* and *IT-CY* values in relation to rubber powder content after 7 days are well described by exponential functions, whereas the results after 28 days are better fitted by linear functions, which are less sensitive to variations in rubber powder dosage.

A qualitative evaluation of the results was carried out with reference to the requirements of Instruction [1] for traffic load categories TC3-TC4. The *ITS* results suggest a permissible rubber powder content of less than 15 %, whereas the *IT-CY* results require more than 20% rubber powder to meet the requirements. At the same time, the *ITS* criterion limits the maximum content of rubber powder to less than 25%, while *IT-CY* permits its increase beyond 25%.

Based on the experiments carried out, the following conclusions were drawn:

1. In terms of *ITS* after 7 days, the following mixtures fulfilled the requirements:
   - 15-20% rubber powder for CEM = 25% or CEM = 30%,
   - 15-25% rubber powder for CEM = 35%.

   For ITS after 28 days, the following mixtures met the requirements:
   - 15% rubber powder for CEM = 25%,
   - 15-20% rubber powder for CEM = 30%,
   - 25% rubber powder for CEM = 35%.
2. With respect to IT-CY stiffness modulus, the requirements were fulfilled by mortars containing 20 ÷ 25% rubber powder with cement contents varying from 25% to 35%.
3. To establish unambiguous requirements for mortar mixtures, the minimum and maximum values of *ITS* and *IT-CY* should be adjusted to ensure that both criteria are assured simultaneously. A proposed requirements for CSR mortars tested at 5°C after 28 days are as follows: *ITS* = 0.6 ÷ 1.3 MPa and *IT-CY* = 3000 ÷ 10000 MPa.
4. Based on the conducted tests, two compositions can be recommended, which yielded comparable *ITS* and I*T-CY* results and correspond to the highest rubber powder dosage at both the minimum and maximum cement contents:
   - 20% rubber powder, CEM = 25%,
   - 25% rubber powder, CEM = 35%.

5. The water resistance tests, expressed as residual indirect tensile strength after water storage, demonstrated that all tested CSR mortars met the specified requirements *ITSR* > 0.8 regardless of composition.
6. Selected, the most promising CSR mortars are to be used in further research on asphalt-cement concretes (ACC).

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Optymalizacja składu zapraw cementowo-piaskowych modyfikowanych drobnoziarnistym miałem gumowym ze względu na właściwości mechaniczne

Streszczenie: Artykuł przedstawia rezultaty pracy badawczej, której celem było ustalenie ilości dodatku miału gumowego 0/1 mm do zapraw cementowo- piaskowych (CPG) stosowanych w betonach asfaltowo-cementowych (BAC) tak, aby spełnić wymagania do mieszanek mineralno-cementowo-emulsyjnych (MMCE), ze względu na brak przepisów dotyczących tych betonów. W pracy zamieszono wyniki badań wytrzymałości na pośrednie rozciąganie (ITS) i modułów sztywności (metodą IT-CY) w temperaturze 5°C wykonane po 7 i 28 dniach. Krzywe regresji badań ITS i IT-CY w zależności o ilości miału gumowego po 7 dniach dobrze opisują funkcje wykładnicze, natomiast w badaniach po 28 dniach funkcje liniowe. Zaobserwowano, że spełnienie granicznych wymagań ITS wyklucza mieszanki spełniające wymagania IT-CY i odwrotnie. W celu jednoznacznego określenia wymagań do mieszanek zapraw zaproponowano wartości minimalne i maksymalne *ITS* i *IT-CY*, aby próbki spełniały oba wymagania jednocześnie. Uzupełnieniem były badania odporności na działanie wody.

Słowa kluczowe: miał gumowy, recykling, zaprawy cementowo-piaskowe.