THE INFLUENCE OF MOISTURE ON THERMAL CONDUCTIVITY OF CONCRETE WITH RECYCLED AGGREGATE

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ABSTRACT

Today, using waste and recycled aggregates in concrete production offers an environmentally friendly alternative to natural aggregates. To identify the true potential of these new materials, a thorough study and understanding of their properties is crucial. In this study, the influence of moisture on the thermal conductivity of concrete samples containing different types of aggregates - natural aggregates, recycled rubber, recycled bricks and ground expanded polystyrene - was analyzed. Each sample was tested at varying moisture levels: 0%, 50%, and 100%. The relationship between moisture, mass, thickness, and porosity of concrete has been examined. The obtained values were then used to analyze the energy properties of a building whose walls are made from tested materials with different thermal conductivity and moisture contents. For all tested samples, the impact of changes in wall moisture on energy consumption and carbon dioxide emissions was assessed. It was determined that concrete made with recycled bricks is the best material for thermal energy conservation and the one with the lowest thermal conductivity value. However, it was observed that samples of concrete with recycled brick and regular brick absorb moisture more quickly compared to concrete made with recycled rubber or standard concrete. So, although the analysis showed that samples with low density and high porosity offer better thermal performance, such materials tend to absorb moisture significantly, which in turn alters their thermal properties and increases energy consumption in buildings.

KEYWORDS _ *Concrete, Energy consumption, Moisture, Recycled aggregates, Thermal conductivity*

INTRODUCTION

As the population increases, so does the need for more construction. With the growing number of buildings being constructed, the demand for energy to maintain thermal comfort levels in buildings also rises. In the European Union, the building sector has therefore been recognised as crucial to achieve energy and climate goals [1]. According to Energy Performance of Buildings Directive [1], it is essential to achieve a zero-emission and fully decarbonised building stock until 2050.

Today, the most widely used material in building construction is concrete [2], [3]. The production of concrete requires certain ingredients, such as cement, water, and aggregate-gravel of different fractions. The largest component of concrete is aggregate [4]. In production of concrete, one way to comply with sustainable practices is to partially replace natural aggregate with recycled one. Additionally, to reduce building energy needs, lightweight concrete, particularly one with recycled aggregate, has been recognized as an effective material for enhancing the thermal insulation performance of structures [5]–[7]. Real et al. [8] found that the use of structural lightweight aggregate concrete (SLWAC) in buildings across European countries can lead to a 15% reduction in heating energy consumption compared to normal weight concrete (NWC).

The mechanical and thermal properties of concrete are significantly influenced by the presence of voids within its structure [9]. Variations in the specific properties of concrete result in differing values of thermal conductivity. Asadi et al. [10] have extensively reviewed and analyzed key parameters that affect the thermal conductivity of cement-based materials as well as the techniques most commonly used to measure the thermal conductivity of concrete. According to their study changes in humidity, temperature, type of aggregate, use of phase change materials (PCMs), type of cementitious material, and density can cause different thermal conductivity values. Kim et al. [11] examined the impact of seven factors on the thermal conductivity of cement paste, mortar, and concrete. These factors include the specimen's humidity conditions, age, temperature, water-cement (w/c) ratio, fine aggregate content, type of admixture, and total aggregate volume fraction. Moisture, the condition of the specimen, and the aggregate volume fraction were identified as the primary factors influencing the thermal conductivity of concrete. However, for mortar and cement paste, the w/c ratio and the type of admixture were found to be the most significant factors affecting the k-value. Similarly, for lightweight concrete, studies have shown that thermal conductivity is largely governed by density [12], loading temperature, and the water-cement (w/c) ratio during the initial hydration phase [13].

In buildings, the thermal and energy performance is highly dependent on the quality of the envelope, particularly on the thermal resistance of the materials used. Given that concrete is commonly used in the construction of building envelopes, understanding and optimizing its thermal conductivity is crucial for enhancing overall energy efficiency. This research investigated how varying moisture levels affect the thermal conductivity of concrete incorporating different aggregate types, including natural aggregates, recycled rubber, and a combination of recycled brick and ground expanded polystyrene. The samples were subjected to moisture conditions of 0%, 50%, and 100%. The study explored the interrelationship between moisture content, mass, thickness, and porosity of the concrete. The acquired data was subsequently utilized to assess the energy performance of a building constructed with walls made from these materials, each exhibiting different thermal conductivities and moisture levels. Additionally, the impact of moisture variation in the walls on energy consumption and carbon dioxide emissions was evaluated for all tested samples.

MATERIALS AND METHODS

Materials

In this paper, self-compacting concrete (SCC) was evaluated due to its potential in masonry unit production. SCC is recognized for its advantages over conventional concrete, as it allows for

similar flexibility in mix design while providing additional benefits that enhance both environmental sustainability and ease of fabrication. Notable advantages include enhanced durability, the elimination of the need for vibration, which simplifies the mold-filling process and improves the quality of the finished surface, as well as a reduction in the risk of aggregate segregation [14].

The relationship between moisture content, mass, thickness, and porosity of conventional concrete and concrete with various aggregates, such as concrete with 10% and 15% recycled rubber, and concrete with recycled brick and expanded polystyrene, was investigated. The experiments were conducted at different moisture levels (0%, 50%, and 100%) to assess the effects on the concrete properties.

To investigate the influence of moisture on the thermal conductivity, four different self-compacting concrete mixtures were analysed. The self-compacting concrete (SCC) mixes were produced in accordance with the recommendations outlined in the European guidelines for self-compacting concrete [15] with the aim of achieving a low-strength SCC as defined by ACI.

In the first mixture of self-compacting concrete, natural aggregates were substituted with a combination of recycled crushed clay bricks (RB), and ground expanded polystyrene (GEP) - mixture SCC RO [16]. Recycled clay bricks and ground expanded polystyrene were used in combination, with the crushed clay bricks obtained as industrial waste, and the expanded polystyrene being mechanically recycled. Optimal mixture composition chosen for testing is presented in Table 1. In mixture SCC RO, brick dust (BP) was used as filler. The mixture included additives in the form of a viscosity-modifying admixture (VMA), superplasticizer (SP), and air-entraining admixture (AEA).

Table 1: RO mixture composition, in kg/m3 [16]

Mixture	Cement	Lime	Water	Additive			Filler		Fine		Coarse	
				SP (%)	VMA (%)	AEA	BP	DP	RB	GEP	RB	GEP
SCC RO	200	255	215	2	0.5	1%	137	-	346	9.6	262	-

The properties of fresh lightweight RO mixture, such as density, air content, flow ability, flow rate, and passing ability, were tested in accordance with EN 12350 and are presented in Table 2.

Table 2: Properties of RO mixture in the fresh state [16]

Mixture	Density ρ (kg/m³)	Air content	Slump-flow test T500 (s)	J-ring test (mm)
SCC RO	1730	8.0	4.8	9.25

Additionally, three SCC mixtures were made with different replacement levels of natural fine aggregate (0%, 10%, 15% of total aggregate volume) with crumb rubber (CR) and cement (0%, 5%, and 10% by mass) with silica fume (SLF).

The reference mix with 0% rubber granulate and 0% silica was labelled as SCC RR. The replacement of natural aggregate with recycled rubber was tested at 10% (SCC RG10) and 15% (SCC RG15) of the total aggregate volume. The concrete mix composition is presented in Table 3. In the mix with a 15% rubber aggregate replacement, 5% silica fume was also added to maintain the desired mechanical properties of the concrete (compressive strength and modulus of elasticity). The self-compacting concrete mixes were designed to maintain a constant water to binder ratio (w/b) of 0.4 and a total binder content of 450 kg/m³ [17]. The water to powder ratio (w/p) was 1.07 and 1.05 for the self-compacting concrete mixes with 0% and 5% of silica fume, respectively, in accordance with the allowable values specified in the European guidelines for self-compacting concrete [17]. The

percentage distribution of the aggregate fractions of 0-2, 0-4, 4-8, and 8-16 mm was 20%, 35%, 20%, and 25%, respectively, of the total aggregate amount [17]. The dosage of superplasticizer (SP) was kept constant for all mixes, while viscosity-modifying admixture (VMA) was only used in the concrete mixes with silica fume, where segregation was observed.

Table 3: SCC RR mixture composition [17]

Mixture	Cement	SLF	Filler	Fine aggregate	Coarse aggregate	Crumb rubber	w/b	SP (%)	VMA (%)
SCC RR	450.0	0.0	80	941.61	817.65	0.00	0.4	1.25	0.24
SCC RG10	450.0	0.0	80	765.59	817.65	66.24	0.4	1.25	0.24
SCC RG15	427.5	22.5	80	674.46	813.87	98.91	0.4	1.25	-

Methods

The testing of thermal conductivity for analyzed concrete samples was conducted using the FOX 200 device in combination with the WinTherm software. Measurement included definition of upper and lower surface temperatures, i.e. during each temperature variation a temperature difference of 10 °C was maintained. Before testing, each sample was stored in an environment specifically designed to prevent moisture absorption.

The experiments were conducted at different moisture levels (0%, 50%, and 100%) to assess the effects on the thermal conductivity of concrete. While 0% and 100% represent theoretical extremes, the 50% condition was included to reflect more realistic in-use moisture levels. This approach allows for a more comprehensive understanding of how varying moisture content influences thermal conductivity in different concrete mixtures. The tested samples were organized in pairs (two samples were tested of each mixture), including conventional/reference concrete (SCC RR), concrete with 10% recycled rubber (SCC RG10), concrete with 15% recycled rubber (SCC RG15), and concrete containing recycled brick and ground expanded polystyrene (SCC RO) [18]. The samples were dried in an oven to achieve a completely dry state. After the initial testing of the samples at 0% moisture content, the specimens were immersed in a water bath and left for four days to allow for complete moisture absorption. Following the immersion period, the samples were removed from the bath, left to stand in ambient air for 30 minutes to eliminate surface water, gently wiped, and subsequently weighed to determine their mass. Subsequent testing was performed on the samples once they reached approximately 50% moisture content. Samples with lower density and higher porosity exhibited a faster reduction in mass; in some cases, specimens achieved approximately 50% moisture content solely through exposure to air. In contrast, other samples required additional drying in an oven under various elevated temperature conditions and time intervals.

RESULTS AND DISCUSSION

Measured Thermal Conductivity Values of Hardened SCC

The samples were tested under three different thermal conditions, each defined by a constant temperature gradient of 10 °C. In the first case, the top plate was maintained at 25 °C and the bottom plate at 15 °C; in the second, 20 °C and 10 °C respectively; and in the third, 15 °C and 5 °C. Prior to testing, the thickness and mass of each sample were accurately measured to ensure consistent and reliable thermal conductivity analysis, Table 4. Based on obtained results, for each tested sample, a representative (i.e., most conservative) average thermal conductivity value was adopted for further analysis and is presented in Table 5.

Table 4: Samples thickness and mass

Moisture / Mixture	0%		50%		100%	
	Thickness (cm)	Mass (g)	Thickness (cm)	Mass (g)	Thickness (cm)	Mass (g)
SCC RR/1	2.558	1035.50	2.558	1066.5	2.558	1097.5
SCC RR/2	2.545	1028.50	2.545	1060.5	2.545	1091.5
SCC RG10/1	2.570	1007.20	2.570	1036.0	2.570	1064.0
SCC RG10/2	2.610	998.49	2.610	1026.5	2.610	1056.0
SCC RG15/1	2.043	740.56	2.043	764.5	2.043	788.0
SCC RG15/2	2.043	733.04	2.043	756.0	2.043	778.0
SCC RO/1	2.055	632.68	2.055	701.5	2.055	771.0
SCC RO/2	2.173	645.56	2.173	717.0	2.173	788.0

Moisture absorption varied significantly among the samples, with the highest recorded uptake being 142.44 g and the lowest 44.96 g. This variation in water absorption indicates that differences in density and porosity among the samples can substantially influence the overall composition of the material.

Table 5: Average thermal conductivity values, λ W/mK

Moisture / Mixture	0%	50%	100%
SCC RR/1	1.525	1.869	2.089
SCC RR/2	1.525	1.763	1.870
SCC RG10/1	1.396	1.492	1.604
SCC RG10/2	1.490	1.561	1.784
SCC RG15/1	0.995	1.171	1.155
SCC RG15/2	1.111	1.190	1.282
SCC RO/1	0.419	0.698	0.827
SCC RO/2	0.405	0.618	0.797

The conducted experiments revealed that, under both fully saturated and completely dry conditions, concrete incorporating recycled brick and ground expanded polystyrene exhibited the most favourable thermal performance. This can be attributed to its high porosity and lower density, which contribute to reduced thermal conductivity. Despite their higher moisture absorption, these materials also release moisture quickly, resulting in more stable thermal behavior. Compared to the reference concrete, which demonstrated the poorest insulating properties in this study, the SCC RO proved to be more effective in retaining heat and reducing potential energy consumption. Rubberized concrete mixtures showed improved performance compared to reference concrete, particularly in dry conditions, due to the inclusion of thermally less conductive rubber particles. The relationship between moisture content and thermal conductivity requires careful consideration. The results indicate that as moisture content increases, the thermal conductivity of the material also rises, leading to higher thermal energy demand in buildings, Table 5. This highlights the significant impact of both calculated and actual moisture conditions on energy efficiency and material performance.

Annual Energy Consumption and CO_2 Emissions

Variations in humidity can significantly affect the building's thermal balance, thereby influencing the amount of energy required to maintain the indoor design temperature during the heating season. Therefore, the impact of changes in relative humidity on energy consumption and the associated

carbon dioxide (CO_2) emissions was analyzed. The measurement results obtained were used as material properties for constructing the external walls of the residential building in order to determine the specific annual thermal energy required for heating ($Q_{H,nd}$) and the specific annual carbon dioxide (CO_2) emissions. The specific annual thermal energy required for heating, $Q_{H,nd}$, is the calculated amount of heat that needs to be supplied by the heating system to maintain the internal design temperature within the building throughout the heating period [19]. Furthermore, the specific annual carbon dioxide (CO_2) emission represent the mass of carbon dioxide released into the environment over the course of one year as a result of the building's energy consumption [19]. The walls used in the analysis are plastered on both sides with lime-cement plaster in a 2 cm layer, and the thickness is 25 cm for all samples. The simulated residential part consists of two external load-bearing walls on which tests were conducted, one internal load-bearing wall with a heated room on the other side, and one internal load-bearing wall with an unheated room on the other side, Figure 1.

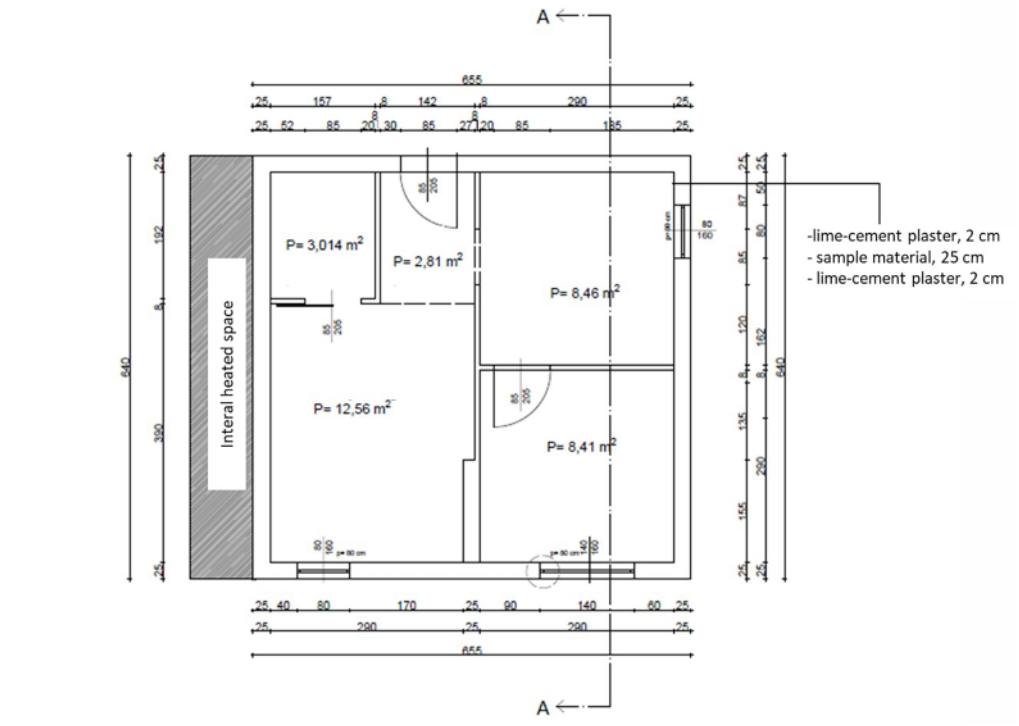


Figure 1: Floor plan of the examined residential section of the building

The walls of the simulated building had thermal conductivity coefficients obtained in the experimental part of the study at 0% and 100% humidity. Along with the measured mass and volume, the density of each sample was determined, which was applied in the computer program for calculating thermal values. It was found that with the increase in sample humidity, both the specific annual thermal energy required for heating and the specific annual carbon dioxide (CO_2) emissions increase as well (Table 6).

Table 6: Samples tested for specific annual thermal energy required for heating and specific annual carbon dioxide (CO2) emissions

Mixture	Moisture	$Q_{H,nd}$ (kWh/m_2 a)	CO_2 emission (kg/m^2 a)	Difference $Q_{H,nd}$	Difference CO_2
SCC RR/1	0%	210.19	63.24	6.9%	5.1%
	100%	225.72	66.64		
SCC RR/2	0%	210.19	63.24	4.7%	3.4%
	100%	220.48	65.48		
SCC RG10/1	0%	205.48	62.25	3.4%	2.4%
	100%	212.74	63.81		
SCC RG10/2	0%	208.83	62.94	4.3%	3.1%
	100%	218.20	64.97		
SCC RG15/1	0%	187.05	58.30	4.2%	2.9%
	100%	195.25	60.05		
SCC RG15/2	0%	193.04	59.56	3.9%	2.7%
	100%	200.89	61.24		
SCC RO/1	0%	142.98	49.05	19.3%	12.7%
	100%	177.14	56.19		
SCC RO/2	0%	141.51	48.73	19.2%	12.6%
	100%	175.05	55.75		
	100%	200.89	61.24		

The conducted testing revealed that concrete with 10% recycled rubber (SCC RG10) exhibited the smallest change in the amount of annual thermal energy required for heating the selected building, as well as in CO_2 emissions, during the humidity variation from 0% to 100%. This type of concrete proved to be the most suitable material for building elements in terms of density, load-bearing capacity, porosity, and other material properties. Concrete with recycled brick and ground expanded polystyrene (SCC RO) showed the best performance in terms of thermal properties and CO_2 emissions, with a notably low specific annual thermal energy requirement for heating, which is 37.3% lower compared to reference concrete (SCC RR). Additionally, the specific annual carbon dioxide emission is 26.88% lower compared to the reference concrete (SCC RR).

CONCLUSION

Thermal conductivity testing of various concrete samples revealed that concrete containing recycled brick and ground expanded polystyrene demonstrated the lowest thermal transmittance and the highest potential for thermal energy retention. Specifically, this material outperformed conventional reference concrete by 73.44% in terms of thermal performance. Following initial testing at 0% moisture, the samples were saturated to simulate real-world exposure to environmental moisture, such as rain or snow. It was observed that samples made with recycled and traditional brick absorbed significantly more moisture—on average 52.90% more than standard concrete—while rubberized concrete showed a more moderate increase of 17.32%.

The increase in moisture content notably affected the thermal conductivity of the materials. Between 0% and 50% moisture, conductivity changed by an average of 20%, with the most pronounced variations seen in brick-based samples. Between 50% and 100% moisture, the average change was 11.81%. Samples with lower density and higher porosity exhibited better thermal insulating properties in dry conditions but absorbed more moisture, which in turn negatively affected their thermal performance and increased potential energy consumption in buildings.

Among all tested materials, the sample containing 10% recycled rubber provided the most balanced performance, combining favourable thermal conductivity, reduced CO_2 emissions, satisfactory mechanical strength, and lower moisture absorption. This makes it the most suitable material for energy-efficient building insulation applications.

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