Innovative Infrastructure Solutions (2020) 5:61
https://doi.org/10.1007/s41062-020-00311-0

PRACTICE-ORIENTED PAPER

Effectiveness of using rubber waste as aggregates for improving thermal performance of plaster-based composites

Abdelaziz Meddah[1] · Hamza Laoubi[2] · Madani Bederina[2]

Received: 31 March 2020 / Accepted: 4 June 2020

Abstract

In this paper, rubber waste is added to plaster-based composite to produce an alternative construction material. The main goal of this study is to investigate the effectiveness of using shredded rubber waste as aggregates in plaster mortar for improving its insulating aspect potential. This composite is obtained by mixing dune sand, plaster, rubber particles, and water. The rubber aggregates are incorporated in mixes as a partial replacement by volume of some parts of sand. Unit weight, capillary absorption of water, mechanical, and thermal-related properties are evaluated and compared according to the percentage of rubber in the mix. The results obtained showed that the addition of rubber will modify the properties of the mortar. Even though the mechanical strength is decreased with the increase of rubber content, it should be mentioned that rubber particles could significantly reduce the weight the material, decrease the rate of water absorption, and improve the insulation aspect of the composite. It can be noted that, below 50% of rubber, modeling by auto-coherent homogenization confirms the experimental results of thermal conductivity. Finally, it should be noted that recycling of rubber waste can produce an alternative eco-friendly material.

Keywords Rubber waste · Plaster mortar · Thermal insulation · Recycling · Composite

Introduction

Recently, studies in construction material sectors are oriented toward the production of eco-friendly materials to reduce the environmental impacts of classic materials and create a sustainable product. The use of these materials in construction can reduce the use of non-renewable natural sources, minimize pollutant emissions, and enhance energy recovery [1]. Moreover, lightweight materials are commonly used in buildings for non structural elements such as wall surface finishing and decorating elements, so the materials will be used for these purposes which do not require highly strengths. Therefore, other properties have priority for these applications such as low density, high porosity, and low thermal conductivity. The main reason for the use of such materials is to improve thermal insulation efficiency and reduce the implementation energy [2]. Although, it is stated that more of 30% of total final energy use is consumed in buildings. Actually, in European Union the newest strategies are consisted to improve the thermal envelope performance in buildings by increasing of insulation aspect potential. This measure is the most effective procedure to drastically minimize the energy used for heating/coaling in extreme weather conditions [3, 4].

Plaster-based materials are considered as porous media with disordered structures composed mainly of entangled gypsum crystal. The interaction of entanglement with inter-crystal-line creates certain cohesion for hardened plaster [2]. This specific structure even offers other attractive advantages, such its acoustic/thermal insulation and fire resistance [5]. Many additives are used by researchers to lighten the plaster-based composites and improve its thermal performance, including date palm fibers [6], expended polystyrene [2, 7], and end-of-life tires derived waste [8]. In these investigations, authors have stated that the mechanical properties of the studied materials are decreased due to the incorporated elements, while the thermal-related characteristics are improved.

Abdelaziz Meddah
abdelaziz.meddah@univ-msila.dz

[1] Civil Engineering Department, LMMS, University of M'sila, P.O. Box 166, 28000 Ichbilia, Msila, Algeria

[2] Civil Engineering Department, SRML, University A. Laghouat, Laghouat, Algeria

Table 1 Chemical composition of plaster

Element	SiO_2	AlO_3	Fe_2O_3	Cao	MgO	SO_2	Na_2O	KO	Cl	LOI
%	0.7	0.1	0.08	36.15	0.53	52.95	0.09	0.03	0.002	5.59

Since civil engineering structures consume a huge volume of natural aggregates, indeed, it is very useful to incorporate industrial wastes, such rubber, in construction material industry, so this procedure can help in reducing the environment impacts of such type of waste and rationalizing the use of natural aggregates which are very rare or very expensive in certain regions.

Rubber waste material is pollutant, not biodegradable, and may create an enabling environment for breeding rats, vermin, and mosquitoes [9, 10]. Rubber-derived wastes can be used in various civil engineering applications due to their advantages. It exhibits high resilience and ductility as well as a very good impermeability. Rubber waste could be used in concrete/mortar composites as aggregates [11, 12] and reinforcements for geotechnical purposes [13]. Baluanini et al. [14] have stated that rubber material may be used in civil engineering for filling, draining, and insulating. Additionally, the incorporation of rubber waste in construction materials helps to consume huge quantities of such type of industrial waste and creates an eco-friendly material.

In this investigation, dune sand, rubber waste, and plaster as binder are mixed to obtain a new composite. The main goal of this work consists of improving the insulation aspect of a plaster mortar to use it as construction material in the south of Algeria which is characterized by high temperatures, especially in summer. The novelty of this approach lies in recycling rubber waste and valorizing local dune sands that are available in huge quantities in this region. Environmentally, the study aims to create a new alternative application for the management of rubber waste.

Materials

The used plaster is from OASIS_PLATREDE_GHARDIA Factory, Algeria. Its chemical composition is presented in Table 1 and Fig. 1. This plaster is composed mainly of 96% of calcium sulfate dihydrate ($CaSO_4$, $2H_2O$) and classified into Class I in accordance with the recommendation of CNERIB [15]. Otherwise, this plaster is considered as coarse plaster according to NFB 12-301, because the percentage of plaster retained by the sieve of 0.8 mm (6.9%) is comprised between 5 and 20%. Dune sand of 0.63 mm maximum diameter and 2596 kg/m^3 of specific density are used for all mixes. The physical properties of sand are summarized in Table 2 and show that it is very clean sand. Its grain size distribution is shown in Fig. 2. Shredded rubber aggregates of 1114 kg/m^3 of density, provided by SAEL factory (SOCIETÉ ALGÉRIENNE DES ELASTOMÈRES), are used in this study. The general aspect of the used rubber is shown in Fig. 3, while its granulometric

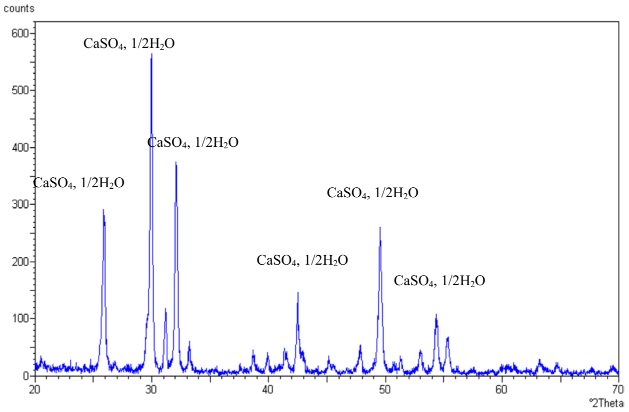

Fig. 1 X-ray diffractogram of plaster

Table 2 Physical properties of materials used

Properties	Sand	Plaster	Rubber
Apparent density (kg/m^3)	1428 ± 14	823 ± 4	1114 ± 14
Specific density(kg/m^3)	2596 ± 26	2521 ± 5	491 ± 26
Compacty (%)	55 ± 0.1	32 ± 0.5	44.19 ± 0.1
Porosity (%)	45 ± 0.5	68 ± 0.5	55.8 ± 0.01
Sand equivalent (%)	86 ± 0.5	–	–

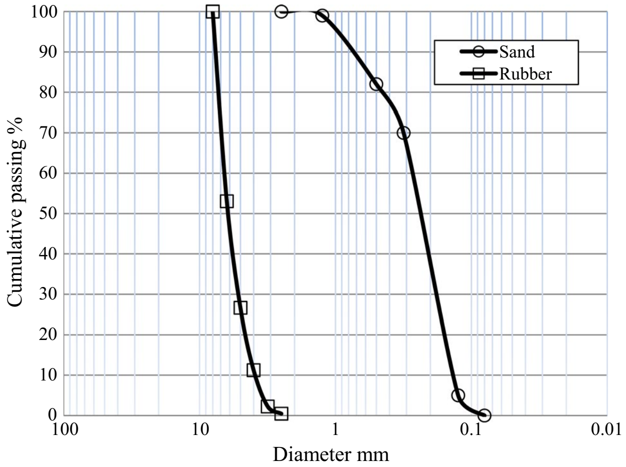

Fig. 2 Particle-size distribution curve of rubber and sand

Fig. 3 Aspect of rubber used

curve distribution is shown in Fig. 2. Air lime is used in this study as a setting retarder for the plaster, because it is susceptible to decrease its solubility and increase its time of use. It should be noted that the mechanical of plaster-based properties will not be affected by adding the lime as reported in many studies [2, 6].

Procedure

To assess the effect of rubber addition on the performance of plaster mortar, six mixes are prepared with different rubber contents: 0, 10, 20, 30, 40, and 50%. The formulation of plaster mortar is carried out according to Algerian guideline recommended by CNERIB (National Centre of Studies and Researchers in Building) [15]. Water-to-plaster ratio (W/P) is fixed at 0.6. According to the recommendation of CNERIB [15], the use of a plaster/sand (P/S) ratio more than 0.5 can negatively affect the mechanical properties of the final product. Hence, P/S is taken equal to 0.5. The rubber aggregates are incorporated in the plaster matrix by partial substitution of dune sand with percentages varying from 10 to 50%. A control sample is elaborated for comparison purposes.

Prismatic specimens of $40 \times 40 \times 160$ mm^3 are used for mechanical characterization, according to EN 13279-2 standards [16]. The absorption rate is determined on cores ($\phi = 100$ mm) as per ASTM C1585 [17]. The molds are filled on three layers without vibration. All test specimens are cured at a temperature of 20 ± 1 °C and a relative humidity of $45 \pm 1\%$ for 28 days. For all tests, the arithmetic mean of three values is taken. To obtain a homogenous distribution of rubber into the mix, reduce the variability of samples, and surpass the problem segregation of lightweight aggregates, the different ingredients are mixed according to the method adopted by Laoubi et al. [2]. The procedure is started by mixing plaster, rubber, and sand at dry state for 30 s. Besides, water is added, and then, the ingredients are mixed at high speed for 30 s.

The thermal properties are measured using the TPS technique (transient plane source). The used test consists in placing, in sandwich, a TPS—probe between two parts of samples and connects it to an electrical circuit, as shown in Fig. 4. The variation of the resistance ΔU between the bounds of a Wheatstone bridge provides an access to the potential difference $\Delta E(t)$ across the TPS element. Consequently, a relationship between $\Delta E(t)$ and the temperature variation in the TPS component can be established. Since the latter is a function of both thermal diffusivity and conductivity, a suitable mathematical processing allows access also to the heat capacity.

Results and discussion

Structural aspect

Figure 5 shows how the ground rubber is distributed in the matrix obtaining, thus, in most of the cases; the material appears compact and relatively homogeneous. The rubber grains seem to be well distributed in the material which reduces the risk of segregation inside the material.

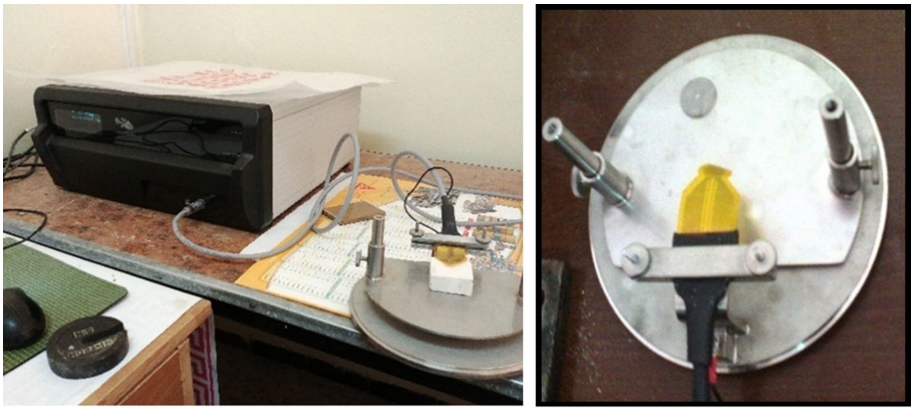

Fig. 4 Measurement of the thermal properties

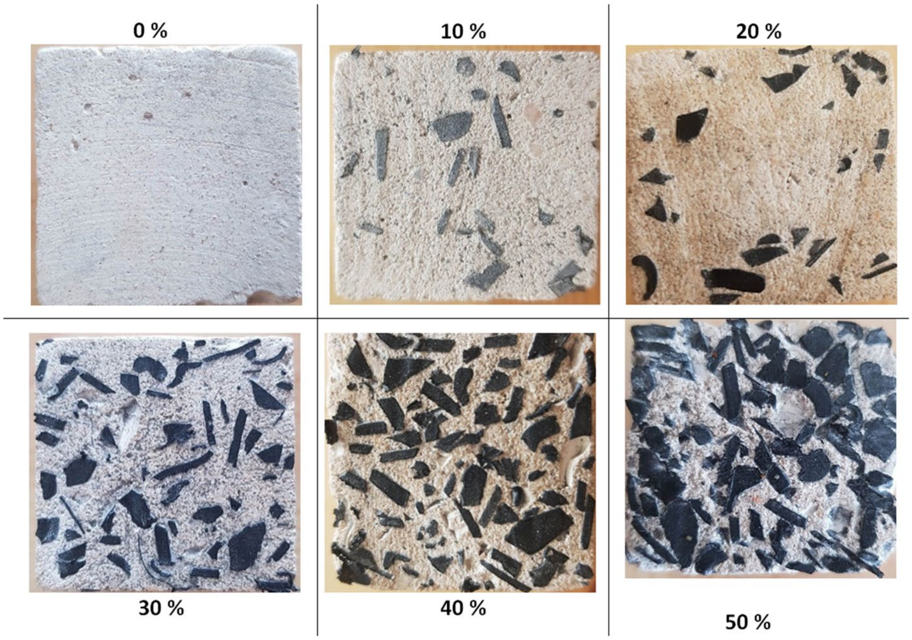

Fig. 5 Visualization of the distribution of rubber grains in the plaster matrix

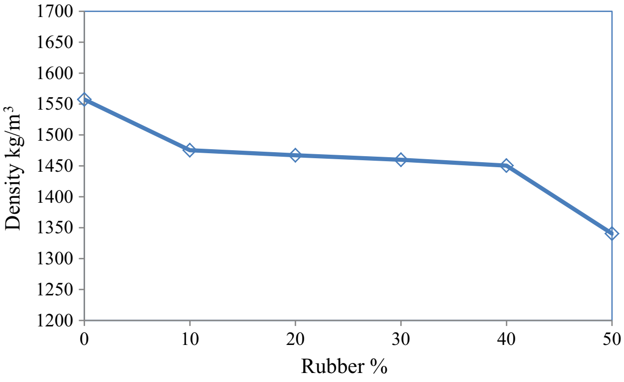

Fig. 6 Effect of rubber on density

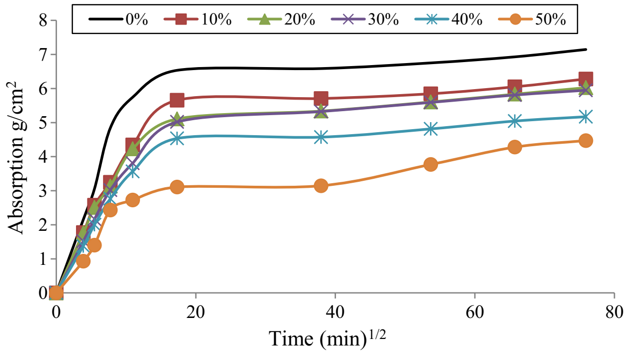

Fig. 7 Effect of rubber on absorption rate

Physical properties

The variation of density according to the percentage of rubber is shown in Fig. 6. It can be noted that the density of mix decreases when the rubber content is increased due the low unit weight of rubber in comparison with the sand substituted. The density is decreased by 9% when rubber is added at rate of 40%. For mix contained 50% of rubber replacement, it is observed that the density drastically decreased (about of 21% in comparison with control mix). Thus, it can be explained by air entrapped with rubber; it is observed during experiments that rubber highly reduces the malleability for this rate of replacement which renders the consolidation of mix more difficult and, consequently, amplifies the volume of voids. Plus, the irregularity decrease observed in density, with the increase of rubber content, is may be due the relatively heterogeneity of rubber waste.

The variation of rate of absorption of water by capillary is evaluated and compared according to the rubber content in the mix and the results obtained are shown in Fig. 7. It can be noted that the partial replacement of sand by rubber considerably decreases the rate of absorption; in fact, the lower absorption ratio of rubber material, in comparison with sand, is responsible for this reduction. Therefore, Benazzouk et al. [18] have reported that rubber particles create closed porosity zones, in which water cannot be penetrated. Other researchers [10, 19] have indicated that rubber reduces the effective area traversed by water, which decreases the absorption rate of rubberized composites. Conversely, some researchers [20–23] have indicated the opposite, rubber aggregates which increase the rate of absorption. They justified this increase by the irregular shape of rubber and the supplementary porosity induced by entrapped air. This variability of results reported in literature in term of absorption for rubberized cement-based materials may be explained by

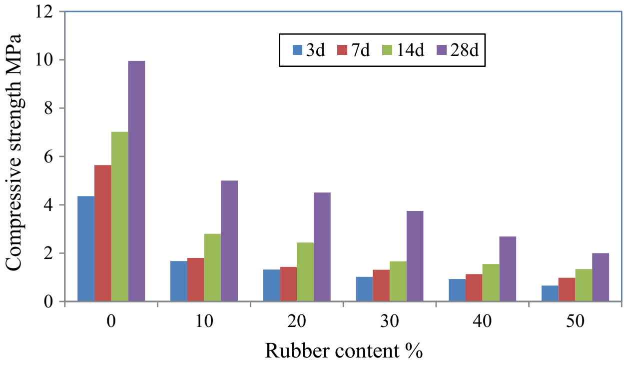

Fig. 8 Effect of rubber content on compressive strength

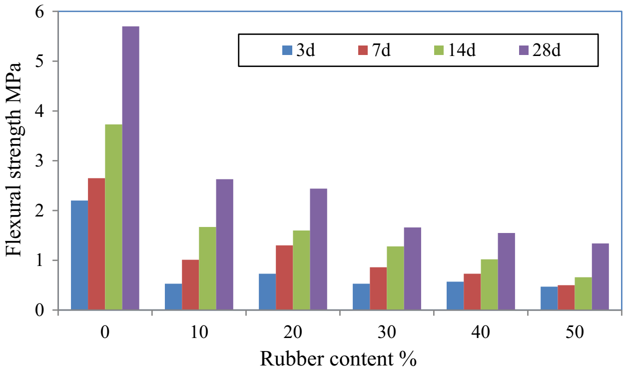

Fig. 9 Effect of rubber content on flexural strength

Fig. 10 Aspect of failed specimens

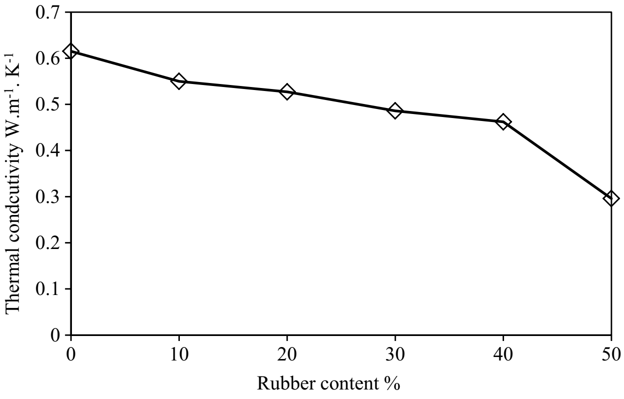

Fig. 11 Variation of thermal conductivity as function of rubber content

the high diversity of rubber aggregates used, the specificity of material, and the test used for quantify this property.

Mechanical properties

Compressive and flexural strengths obtained on rubberized plaster mortar are shown in Figs. 8 and 9, respectively. It can be noted that the compressive and flexural strengths are negatively affected by the incorporation of rubber which indicates that rubber decreases the kinetics of strength development. The results are in agreement with all the investigations reported in the literature [9, 24–26]. Indeed, the losses of strengths in the cases of cement/plaster-based materials caused by the use of rubber are commonly justified by the lower stiffness of rubber material compared to that of sand [27], the reduction in the amount of solid load-carrying material [28], the concentration of stresses at the boundaries of rubber aggregates [28], and the low adhesion between rubber particles and the cement paste [29, 30]. In fact, with increased loading, the failure mechanism starts by disintegrating of rubber from the matrix due to the relatively poor interfacial adhesion. Moreover, it should be noted that for rubberized specimens, the failure mode of the specimens under compressive/flexural loading did not exhibit the typical brittle failure as in the case of mineral aggregates. Therefore, with the presence of rubber, the failure seems to be more gradual and compressible (Fig. 10), which s indicates the high energy absorption capacity of rubberized composites [8, 31].

Thermal properties

To quantify the effect of rubber on the potential of heat transfer, the thermal conductivity coefficient is evaluated for each rubber contents. It should be noted that a regular decrease of thermal conductivity is observed with the rubber content increase in the composite. As indicated in Fig. 11, the thermal conductivity decreased from 0.615 to 0.296 W m^{-1} k^{-1} when rubber replacement is changed from 0 to 50%, which represented a loss of 52% (in comparison with control mix). The decrease of thermal conductivity of rubberized plaster concrete may be justified by the fact that rubber possessed lower thermal conductivity than dune sand. In this sense, several researchers have used this argument to explain the decrease of thermal conductivity of rubberized plaster/concrete based materials. Furthermore, other researchers have also attributed this behavior to the air entrapped by rubber aggregates, which creates closed porosity zones and, consequently, increases the insulation aspect of the material. The obtained values are consistent with those of the literature. In the same vein, Rivero et al. [31] and Herrero et al. [8] have stated the same observation in the case of the addition of rubber obtained from pipe and end-of-life tires to the gypsum composite.

The relationship between the thermal conductivity of the composite and its density is plotted in Fig. 12. It is observed that the thermal conductivity of the composite decreases with the decrease of its density. Thus, this finding confirms the argument mentioned above which indicates that the lightening of the composite with rubber helps to improve the thermal insulation aspect. Plus, these obtained results are in agreement with several works of literature in which several additives are mixed with plaster/concrete composites [2, 7].

Figure 13 shows the evolution of specific heat according to the percentage of rubber in the mix. When rubber content increased, there is a regular increase in the specific heat. The obtained results are in agreement with that stated in the literature. Therefore, it is usually reported that when adding lightweight additives such as vegetal/synthetic fibers and/or wastes to plaster composites, the specific heat is increased [1, 32].

The relationship between the thermal diffusivity and rubber content is also shown in Fig. 13. As for the thermal conductivity, the incorporation of rubber in the plaster mortar decreases its thermal diffusivity. For mix contained about of 50% of rubber, the thermal diffusivity decreases by 88.6% (in comparison with the control mix). The same argument used to justify the decrease of thermal conductivity is still valid for thermal diffusivity. These obtained results are in good agreement with those of the literature [8, 31].

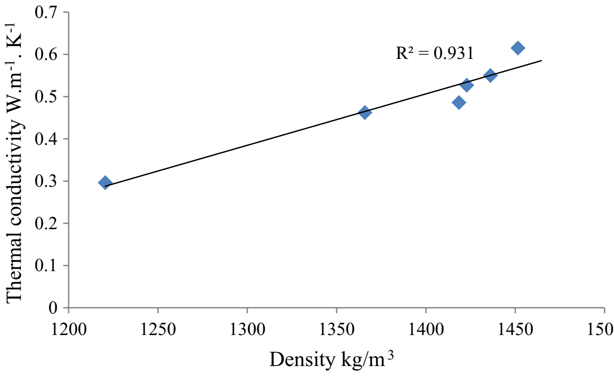

Fig. 12 Relationship between thermal conductivity and density of composite

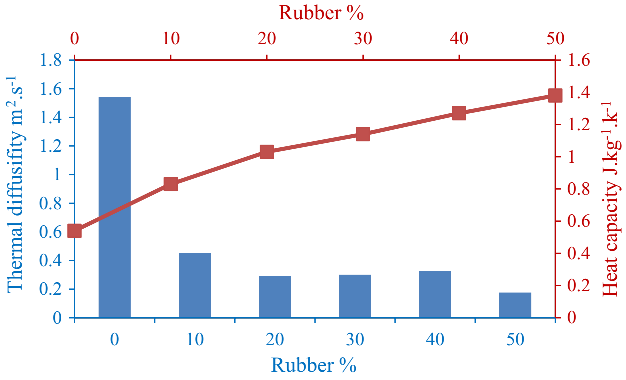

Fig. 13 Effect of rubber content on the thermal conductivity and diffusivity

- Modeling of thermal conductivity by auto-coherent homogenization

The auto-coherent homogenization modeling consists of estimating the thermal conductivity coefficient for a composite material. The principle of this method is based on the transition from thermal conductivity and volume concentration of each component to the biggest scale, in which an equivalent thermal conductivity of composite is expressed. The implementation of auto-coherent homogenization requires two conditions, the separation of scale and the existence of a generic pattern. Furthermore, for this method, it is assumed that the energy is conserved between the heterogeneous medium and the composite will be homogenized if it is submitted to the same boundary conditions [1, 33]. In this context, the generic motif is composed of three components as mentioned in Fig. 14. In fact, the first constituent (air) is modeled by a sphere of radius R_1, thermal conductivity λ_1, and density ρ_1. The second constituent is represented by a spherical cell of rubber with the characteristic (R_2, λ_2,

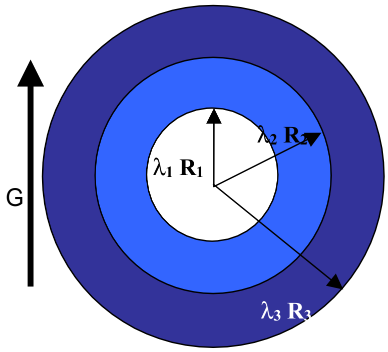

Fig. 14 Principal of self-consistent scheme of a tri-composite cell

and ρ_2). Air and rubber are enveloped by a third sphere (R_3, λ_3, and ρ_3) which represents the solid matrix (plaster and sand). This approach requires the knowledge of volume fractions and thermal conductivities of both rubber particles and matrix. The volume fractions are directly calculated from the mass of each component [33]. The equivalent thermal conductivity (λ_{eq}) for the composite is then calculated by this expression (Eq. 1):

$$\lambda_{\mathrm{eq}} = \lambda_m \left[1 + \frac{\theta}{\frac{1-\theta}{3} + \frac{1+\frac{\delta}{3}\left(\frac{\lambda_a}{\lambda_r}-1\right)}{\frac{\lambda_a}{\lambda_m}-1-\frac{\delta}{3}\left(\frac{\lambda_a}{\lambda_r}-1\right)\left(\frac{2\lambda_r}{\lambda_m}+1\right)}} \right] \tag{1}$$

$$\theta = 1 - \frac{1}{k+1}\frac{\rho}{\rho_m} \tag{2}$$

$$\delta = \frac{\rho}{\rho_r}\frac{k}{(k+1)}\frac{1}{1-\frac{\rho}{\rho_m}\frac{1}{k+1}} \tag{3}$$

$$m_r = K \cdot m_m,$$

where ρ_m and λ_m represent, respectively, the density and the thermal conductivity of matrix, ρ_r and λ_r density and thermal conductivity of the rubber, λ_a thermal conductivity of the ambient air at (20 °C), m_r and m_m masses of rubber and matrix in formulation, respectively, and θ and δ were defined to make it possible to characterize the volume concentrations.

The results obtained by auto-coherent modeling, for the composites studied, are given and compared with the experimental results, as shown in Fig. 15. It clearly can be seen that the theoretical values are very close to experimental data with relative change less than 1%, for mixes containing less than 20% of rubber. For the mixes containing 30 and 40%, the relative change between the theoretical and experimental measurements is less than 7%, while for the mix prepared with 50% of rubber, it is observed that relative change is more than 40%. The variability and dispersion of results between the experimentation and modeling for mixes containing relatively high volume of rubber can be justified by the density of rubber aggregates itself. It is assumed that it is homogeneous material, but, in reality, it is not the case, since, in practice, rubber waste is constituted from different sources. Moreover, it should important to mention that during experiments, it is that the malleability of composite at fresh state was highly affected for the mix contained 50% of rubber which created more voids in the composite and, consequently, increased the porosity.

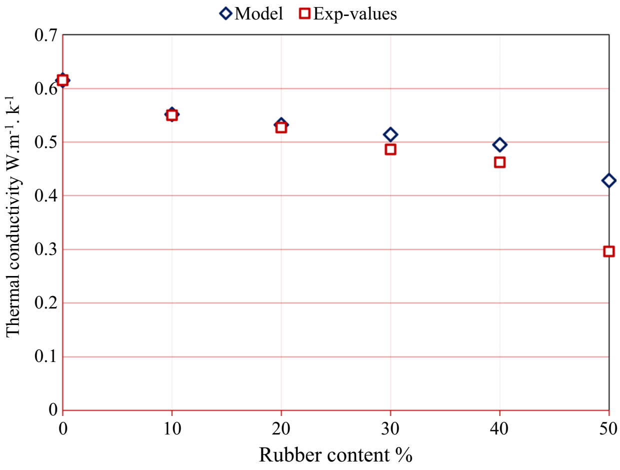

Fig. 15 Comparison between theoretical and experimental data for of the measure of thermal conductivity

Conclusion

This study was undertaken to characterize the mechanical and thermal properties of a new plaster mortar composite. Rubber was added to plaster mortar with different concentrations. Based on the experimental results, these conclusions can be drawn:

- The unit weight of the composite is decreased with the increase of rubber content in the mix. Therefore, rubberized plaster mortar can be considered as lightweight material according to ACI 213R-87.
- The incorporation of rubber reduces the rate of capillary absorption of the composite due to the non absorbent aspect of rubber material. Thus, it can help to improve its durability.
- The compressive and flexural strengths of the composite are decreased with the increase of rubber content. Despite this reduction in term of strength, it can be noted that is always possible to use this material in buildings for non structural elements which do not require high strength.
- The addition of rubber-to-sand plaster composites improved its thermal insulating potential which is advantageous for both prevent heat transfer and saving energy in buildings. It has been proved that both thermal conductivity and diffusivity are decreased, while the heat flow increased as the rubber content is increased in the composite.
- Modeling by auto-coherent homogenization seems to be very effective to estimate the thermal conductivity of plaster rubber-based mortar, provided that the proportion of rubber does not reach 50%.

In addition to that, according to Algerian specifications standard (DTR C3.2), this composite can be used to produce precast plaster panels and wall surface finishing. Finally, to make these results applicable, it is recommended to produce experimental precast panels with rubberized plaster sand composites.

Author contributions All authors contributed to the study conception, mix design, material preparation, data collection, and analysis.

Funding Not applicable.

Availability of data and material (data transparency) All authors declare that all data and materials included in the study comply with field standards.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Code availability Not applicable.

References

1. Djoudi A, Khenfer MM, Bali A, Bouziani T (2014) Effect of the addition of date palm fibers on thermal properties of plaster concrete: experimental study and modeling. J Adhes Sci Technol 28:2100–2111. https://doi.org/10.1080/01694243.2014.948363
2. Laoubi H, Djoudi A, Dheilly RM et al (2019) Durability of a lightweight construction material made with dune sand and expanded polystyrene. J Adhes Sci Technol. https://doi.org/10.1080/01694243.2019.1637091
3. Berardi U (2017) A cross-country comparison of the building energy consumptions and their trends. Resour Conserv Recycl 123:230–241. https://doi.org/10.1016/j.resconrec.2016.03.014
4. Berardi U, Tronchin L, Massimiliano M, Nastasi B (2018) On the effects of variation of thermal conductivity in buildings in the Italian Construction Sector. Energies 11:1–17. https://doi.org/10.3390/en11040872
5. Badens E (1998) Etude de l'adsorption de l'eau sur les cristaux de gypse et de son influence sur les propriétés mécaniques du plâtre pris pur et additive. Université de Aix-Marseille, Marseille, p 3
6. Djoudi A (2015) Etude de la durabilité et du comportement thermo-phonique des bétons de platre renforcés par des fibres végétales du palmier dattier. ENP d'Alger, El Harrach
7. Laoubi H, Bederina M, Djoudi A et al (2018) Study of a new plaster composite based on dune sand and expanded polystyrene as aggregates. Open Civil Eng J 12:401–412. https://doi.org/10.2174/1874149501812010401
8. Herrero S, Mayor P, Hernández-olivares F (2013) Influence of proportion and particle size gradation of rubber from end-of-life tires on mechanical, thermal and acoustic properties of plaster—nrubber mortars. Mater Des 47:633–642. https://doi.org/10.1016/j.matdes.2012.12.063
9. Meddah A, Bali A, Beddar M (2015) Valorization of rubber waste in concrete pavement. In: Beddar M, Meddah A (eds) Journées d'étude de Génie Civil JEGC 2015. M'sila University, Algeria, pp 47–53
10. Meddah A, Beddar M, Bali A (2014) Use of shredded rubber tire aggregates for roller compacted concrete pavement. J Clean Prod 72:187–192. https://doi.org/10.1016/j.jclepro.2014.02.052
11. Meddah A, Beddar M, Bali A (2014) Experimental study of compaction quality for roller compacted concrete pavement containing rubber tire wastes. In: Sustainability, eco-efficiency and conservation in transportation infrastructure asset management—proceedings of the 3rd international conference on tranportation infrastructure, ICTI 2014, Piza, Italy, 22–25 April 2014
12. Meddah A, Bensaci H, Beddar M, Bali A (2017) Study of the effects of mechanical and chemical treatment of rubber on the performance of rubberized roller-compacted concrete pavement. Innov Infrastruct Solut. https://doi.org/10.1007/s41062-017-0068-5
13. Meddah A, Merzoug K (2017) Feasibility of using rubber waste fibers as reinforcements for sandy soils. Innov Infrastruct Solut 2:5. https://doi.org/10.1007/s41062-017-0053-z
14. Balunaini U, Yoon S, Prezzi M, Salgado R (2014) Pullout response of Uniaxial Geogrid in tire shred-sand mixtures. Geotech Geol Eng 32:505–523. https://doi.org/10.1007/s10706-014-9731-1
15. CNERIB (1993) Recommandations pour la construction en platre (Recommendations for construction with Plaster): Cnerib Report. Ministère de l'Habitat, de l'urbanisme et de la ville, Sidi M'Hamed
16. NF-EN13279-2 (2014) Gypsum binders and gypsum plasters—part 2: test methods. NSAI, Washington
17. ASTM C 1585 (2013) Standard test method for measurement of rate of absorption of water by hydraulic-. ASTM Int. https://doi.org/10.1520/C1585-13.2
18. Benazzouk A, Douzane O, Langlet T et al (2007) Physico-mechanical properties and water absorption of cement composite containing shredded rubber wastes. Cem Concr Compos 29:732–740. https://doi.org/10.1016/j.cemconcomp.2007.07.001
19. Meddah A (2015) Caractérisation d'un béton compacté contenant des déchets pneumatiques. ENP d'Alger, El Harrach
20. Ling TC, Nor HM, Lim SK (2010) Using recycled waste tyres in concrete paving blocks. Proc Inst Civil Eng Waste Resour Manag 163:37–45. https://doi.org/10.1680/warm.2010.163.1.37
21. Hesami S, Salehi Hikouei I, Emadi SAA (2016) Mechanical behavior of self-compacting concrete pavements incorporating recycled tire rubber crumb and reinforced with polypropylene fiber. J Clean Prod 133:228–234. https://doi.org/10.1016/j.jclepro.2016.04.079
22. Bisht K, Ramana PV (2017) Evaluation of mechanical and durability properties of crumb rubber concrete. Constr Build Mater 155:811–817. https://doi.org/10.1016/j.conbuildmat.2017.08.131
23. Thakur A, Senthil K, Sharma R, Singh AP (2020) Employment of crumb rubber tyre in concrete masonry bricks. Mater Today Proc. https://doi.org/10.1016/j.matpr.2020.02.106
24. Topçu IB (1995) The properties of rubberized concretes. Cem Concr Res 25:304–310. https://doi.org/10.1016/0008-8846(95)00014-3
25. Khatib ZK, Bayomy FM (1999) Rubberized portland cement concrete. J Mater Civil Eng 11:206–213. https://doi.org/10.1061/(ASCE)0899-1561(1999)11:3(206)
26. Boudaoud Z, Beddar M (2012) Effects of recycled tires rubber aggregates on the characteristics of cement concrete. Open J Civil Eng 02:193–197. https://doi.org/10.4236/ojce.2012.24025
27. Ho AC (2010) Optimisation de la composition et caractérisation d'un béton incorporant des granulats issus du broyage de pneus usagés: application aux éléments de grande surface. L'Insa de Toulouse, France
28. Eldin NN, Senouci A (1993) Rubber-tire particles as concrete aggregtaes. J Mater Civil Eng 5:478–496. https://doi.org/10.1061/(ASCE)0899-1561(1993)5:4(478)

29. Raghavan D, Uynh HH, Fe Rraris CF (1998) Workability, mech anical properties, and chemical stability of a recycled tyre rubber-filled cementitious composite. J Mater Sci 33:1745–1752
30. Segre N, Joekes I (2000) Use of tire rubber particles as addition to cement paste. Cem Concr Res 30:1421–1425. https://doi.org/10.1016/S0008-8846(00)00373-2
31. Rivero AJ, de Báez A, Navarro JG (2014) New composite gypsym-waste rubber from pipe foam insulation: characterization. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2014.01.027
32. Lam K, Oyedun A, Cheung K et al (2011) Modelling pyrolysis with dynamic heating. Chem Eng Sci 66:6505–6514
33. Cerezo V (2005) Propriétés mécaniques, thermiques et acoustiques d'un matériau à base de particules végétales: approche expérimentale et modélisation théorique. INSA de Lyon, Lyon