Valorisation of face mask waste in mortar

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Abstract

In view of the COVID-19 pandemic, most countries in the world have mandated the use of face masks to limit the spread of this dangerous disease. The billions of face masks that are produced around the world to date generate millions of tonnes of plastic waste that is thrown into the environment. The present work aims to valorise single-use masks or surgical masks in mortar. In this work, the effect of substituting 1–5% of the volume of the mortar with pieces of masks of 2 cm² section and 4 cm² section is explored. Mechanically, an increase in compressive strength of between 10 and 20% is noted, as well as an improvement in flexural strength of 19–30%. Physically, the thermal resistance of the mortars formulated from waste mask improved by up to 23%, and there was a clear improvement in the acoustic reflection coefficient for all frequencies. The capillary rise test conducted on the mortar samples shows that the amount of the absorbed water increases. However, although in most cases the presence of mask pieces increases the sorptivity of the mortar, this is not associated with a higher capillary rise. The results found are encouraging, allowing on the one hand to improve the physical and mechanical characteristics of the mortar and on the other hand to solve a dangerous environmental problem.

Keywords Covid19 pandemic · Face masks · Compressive strength · Flexural strength · Thermal conductivity · Capillary rise

Introduction

To deal with the COVID-19 pandemic, more than half of the countries in the world have imposed the use of face masks [1]. Thus, through the use of face masks by the population, the spread of the pandemic has been controlled, but in return, several environmental problems have been caused.

Indeed, the huge quantities of face masks used, estimated at more than seven hundred million per day in Africa and more than 2.2 billion in Asia [2–4], are mostly thrown away in nature, sent to landfill or incinerated. Moreover, with their lightweight nature facilitating their transport by wind and

rainwater in the wild, face masks become noticeable almost everywhere from streets, parks and even beaches.

Single-use surgical masks, the most widely used among face masks, contain mainly polypropylene [5] which is a source of microplastic environmental pollution [6]. Consequently, the global daily production of face masks, estimated at 6.88 billion during the COVID-19 pandemic [4], generates millions of tonnes of plastic waste discarded into the environment, which, due to its non-biodegradable nature, poses a threat to wildlife and marine life [4, 7].

To reduce the environmental risks associated with the disposal of single-use face masks, the recovery of these wastes by using them as artificial aggregates in the production of construction materials is suggested [8].

In this context, Saberian et al. [4] proposed to recycle the single-use face masks in the pavements base by adding different percentages of the shredded face mask to the recycled concrete aggregate. Tests showed that the introduction of the shredded face mask increased the compressive strength, stiffness, ductility, and flexibility of the mixtures.

Kilmartin-Lynch et al. [1] conducted a preliminary study of the utilisation of single-use face masks to improve the mechanical properties of concrete. In their work, single-use

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face masks were cut and five different percentages ranging from 0 to 0.25% of the total volume were considered for introduction into concrete. The results showed that the compressive and tensile strengths were improved. This agrees with the results that the researchers found when adding the plastic material to the concrete.

In recent years, a lot of research has considered the use of plastic waste in a cementitious matrix. Researchers have used different types of plastics such as polyvinyl chloride (PVC), expanded polystyrene foam (EPS), high density polyethylene (HDPE), thermoset plastics, polycarbonate, polyurethane foam, glass reinforced plastics (GRP), polyethylene terephthalate (PET) and polypropylene (PP) [9, 10].

The addition of polypropylene fibres or particles to a cement matrix has been studied by several researchers. If polypropylene is added in the form of particles, the mechanical behaviour deteriorates, and as an example, Faraj et al. [11] studied the mechanical, fracture and durability characteristics of self-compacting high-strength concrete containing recycled polypropylene plastic particles. The compressive and flexural strength of the concrete was significantly reduced with increasing the PP content, whereas the fracture and ductility properties are improved. On the other hand, if the polypropylene is added in the form of fibres as in [12–14], the compressive and flexural strengths may improve.

These results are encouraging and lead the present study to investigate the possibility of recycling single-use face masks in mortars. A series of experiments are being

conducted to evaluate the effect of polypropylene fibres from single-use face masks on mechanical strength, thermal insulation, acoustic reflection and durability.

Thus, the current study aims to provide a better understanding of the effect of the use of mask fibres in mortar while investigating the effect of the dimensions of the textile pieces and the textile dosage.

Materials and experimental procedure

Materials

To prepare the mortar, three materials are used, namely binder, aggregate, and pieces of single-use mask. The cement used as binder is Portland cement CEM I 42.5 characterised by a density of 3210 kg/m^3 , a Blaine specific surface of $346.6 \text{ m}^2/\text{kg}$ and compactness of 0.574. The mineralogical composition of the cement is shown in Table 1.

The aggregate is 0/4 mm sand, with a fineness modulus of 2.08 and a density of 2440 kg/m^3 . The Granulometric curve of the sand is shown in Fig. 1.

Pieces of single-use masks

Generally, a single-use mask or surgical mask consists of three layers which are mainly made of polypropylene. However, other polymers can be used in the production of masks such as polyethylene, polycarbonate, polystyrene or polyester [5, 15].

The interior layer (Fig. 2b) is soft and absorbent and consists of a non-woven fabric that absorbs moisture released by the user. The middle layer (Fig. 2a) is made of a melt-blown material. This layer has the role

Table 1 Mineralogical composition of cement

C ₃ S	C ₂ S	C ₃ A	C ₄ AF
61%	11.85%	2.42%	13.75%

Fig. 1 Granulometric curve of sand

Fig. 2 Microscopic view of the different layers of the mask

of preventing microbes. The outer layer (Fig. 2c, d) is a non-woven fabric designed to isolate liquids sprayed by the user.

It is noted that the microstructure of each layer is different from the others, which suggests a different effect when added to a cement matrix.

Microscopic analysis of the different layers of the mask (Fig. 1) also shows the presence of a multitude of microfibrils superposed in each layer. The presence of voids is also noticed in the outer and inner layer. The voids generally suggest a lower density and higher water absorption of the cement-based composite.

When incorporating fibres into a cementitious matrix, fibre-matrix adhesion plays an important role in improving or degrading mechanical behaviour. Thus, the larger the fibre size, the greater the adhesion to cement. Hence, an improvement in mechanical behaviour is expected. Considering the dimensions of the samples, the largest dimension of mask fibre chosen is 2 cm. This dimension, although relatively large, the fact that the mask pieces are flexible and will bend during mixing, does not cause any problem of implementation. The effect of the dimensions can be seen from the

comparison of the results of the mortars comprising the pieces of dimensions $2 \times 2 \text{ cm}^2$ and $2 \times 2 \text{ cm}^2$.

Thus, the single-use masks are first prepared by removing the earrings and nose wire; then, they are cut into two sizes: $1 \times 2 \text{ cm}^2$ and $2 \times 2 \text{ cm}^2$ (Fig. 3).

The results of the water absorption measurements of the fibres, presented in Fig. 4, show a significant and rapid water absorption by the masks. Indeed, the saturation state can be reached in 10 min by the mask pieces with an absorption of more than 90% of their dry weight. Therefore, to avoid possible absorption of mixing water, the mask pieces are placed in water for at least 15 min before use. After that, they are placed on an absorbent surface to remove excess water from their surfaces.

Measurement of the density of the saturated mask pieces shows that they are characterised by a density of 301 kg/m^3 .

Preparation of the mortar

The mask pieces were added to the mortar, substituting 1, 2, 3 and 5% of the volume of sand with the same volume of fibres. In addition to the specimens without waste masks,

Fig. 3 Masks pieces

Fig. 4 Water absorption of mask pieces

Table 2 Mortar composition (kg/m³)

Formulation	Sand	Fibre	Cement	Water
M ₀	1450	0	450	225
M ₁	1435	1.63	450	225
M ₂	1419	3.26	450	225
M ₃	1406.5	4.89	450	225
M ₅	1373	8.15	450	225

five sets of mortar specimens with fibres were cast. The composition of the different mixes is shown in Table 2. For each formulation, two sizes of mask pieces are incorporated; one is denoted by M_{is}, the mixtures containing pieces of masks of 2 cm² in size, and the other is denoted by M_{il}, those containing pieces of 4 cm² in size, where *i* is the percentage of fibre.

The development of the mortar with pieces of mask begins by mixing the cement and water manually; then, the pieces of mask are introduced progressively into the mixture.

Next, the sand is introduced progressively while maintaining manual mixing to homogenise the different components of the mixture. Then, an automatic mixing is carried out in a mixer during 1mn30s, then a manual mixing during 30 s and finally an automatic mixing during 1mn30s (Fig. 5).

The mixed materials are introduced into the moulds and compacted with an impact device to avoid voids in the moulds. Prismatic specimens, with the dimensions 40×40×160 mm³, are produced for the bending and compression measurements and for the capillarity measurement.

For the thermal test, specimens with the dimensions 50×50×300 mm³ are produced. For the acoustic test, the specimens are cylindrical with a diameter of 100 mm and a thickness of 50 mm.

After 24 h of mortar production, the test specimens are removed from the mould and placed in a water tank until 24 h before testing (Standard EN 12390-2 [16]).

Experimental methods

Four prismatic specimens with the size 40×40×160 mm³ are prepared for the mechanical properties of each mortar formulation. The mechanical strength is evaluated using three-point flexural and compression tests in accordance with NF EN 196-1 standard [17].

For the characterisation of the hydric behaviour, the capillary absorption test is performed (standard NF EN 13057 [18]). For each formulation, the capillary water absorption is determined on three specimens of dimensions 40×40×160 mm³ older than 28 days. These specimens are initially dried for 24 h at a temperature of 105°. Then, the side faces of the specimens are waterproofed by applying a layer of paraffin to ensure unidirectional water flow. The test specimens are then weighed and placed in a container with the transverse face in contact with water to ensure water flow. In the testing device, the water level is automatically adjusted so that the cross-sectional area immersed in water remains at a constant depth of 2 mm for the duration of the test.

During the test, each sample is weighed, and the height of the rise of water is measured on the side face after 30 min, 1 h, 2 h, 4 h, 8 h and 24 h from the beginning of the test. The experimental set-up used, similar to that described in [19], is given in Fig. 6.

For the thermal conductivity, three prismatic samples of size 50×50×150 mm³ of each mortar formulation are prepared. The conductivity measurement is elaborated using a Heat flow meter Fox 314 according to ASTM C518 [20] and ISO 8301 [21] standards.

The impedance tube is used for the evaluation of the absorption coefficient on cylindrical samples with 100 mm diameter.

Fig. 5 Preparation of the mixture

Fig. 6 Experimental set-up scheme for the capillary test

The absorption coefficient is measured according to ASTM E1050:2008 [22] and ISO 10534-2:1998 [23] standards in the frequency range between 125 and 4000 Hz.

Results and discussion

Before the mechanical characterisation of the different mortars, the density of the different mixes is measured. It is noted that the effect of the introduction of the mask pieces on the density of the mortar is minimal. Indeed, if the density of the mix without fibres is 2155 kg/m^3 , it varies between 2142 and 2090 kg/m^3 for the mortars with fibres. This is mainly due to the small amount of mask introduced in the mixes.

Compressive strength

Table 3 shows the average compressive strength and the standard deviation values of the different mortar compositions at 28 days. It is noticed that the introduction of the mask pieces increases the compressive strength values, mainly for the small size fibres. The maximum increase for the $2 \text{ cm} \times 1 \text{ cm}$ size is 10% obtained for a 5% quantity of mask pieces. The increase for the $2 \text{ cm} \times 2 \text{ cm}$ size is about 20% for 1% mask pieces, and 18% for 3% mask pieces.

Table 3 Compressive strength at 28 days (MPa)

Mask pieces quantity (%)	4 cm ² mask pieces		2 cm ² mask pieces	
	Av	S.D	Av	S.D
0	30.68	0.78	30.68	0.78
1	29.31	1.21	37.08	2.24
2	32.08	0.79	34.94	0.51
3	31.45	1.26	36.29	2.32
5	33.72	0.72	33.14	2.04

Fig. 7 Compressive strength at 28 days

Figure 7 shows that despite the increase in compressive strength compared to the reference mix (M0), its evolution as a function of the amount of mask pieces added is not regular. This can be explained by the fact that the three layers of masks do not have the same properties, and that it is not possible to ensure that the ratio between the quantities of the different layers is constant in all mixes and in all specimens.

The improvement or degradation of the compressive strength when adding plastic waste to the mortar or the concrete can be due to many factors. Among these factors is the distribution of fibres within the matrix.

The proper distribution of fibres within the mix leads to the reduction of pores within the matrix [24]. Thus, the fibres reduce the micro-cracks, and consequently, the cracks need more applied energy to propagate in the specimen. This results in improved compressive strength.

On the other hand, if the matrix is very compact, such as the case of high-strength concrete where pores are present with a minimum ratio, the addition of the fibres to the concrete produces pores which create a zone of weakness within the concrete and, consequently, cause the propagation of cracks [25].

In addition, the soft nature of fibres compared to natural aggregates is a factor that weakens the strength of concrete [26]. Indeed, during loading, the plastic behaves as voids within the matrix, resulting in crack initiation around the fibres.

The adhesion between the plastic fibres and the cementitious matrix is also a parameter that influences the compressive strength.

In summary, the influence of the introduction of plastic waste on the strength of concrete depends on the presence of additional voids within the concrete due to the presence of the fibres, the adhesion between the plastic fibres and the cementitious matrix and the ability of the fibres to arrest crack openings.

Several researchers obtained similar results to the present study by adding polypropylene fibres to concrete. As an example, Patel et al. [27] found that the compressive strength improved by up to 16% over concrete without fibres with the addition of 1.5% and 2% polypropylene.

Tests by Kakooei et al. showed that the compressive strength of concrete with polypropylene fibres increased with increasing amount of polypropylene up to 2 kg m³ [12].

Flexural strength

Table 4 shows the effect of the addition of the single-use mask pieces on the flexural strength. Overall, the introduction of the mask pieces into the mortar increases the flexural strength compared to the reference mortar.

It is observed in Fig. 8 that in general, the mortar reinforced with larger pieces of masks has a higher flexural

Fig. 8 Flexural strength at 28 days

strength. Indeed, for the small size of the mask pieces, the increase in flexural strength does not exceed 19% obtained for 5% of fibres; however, for the large size of mask pieces, this value exceeds 30% for 1 and 2% of fibres.

The increase in flexural strength with the incorporation of polypropylene fibres could also be observed in several other studies done on concrete and cement mortars [14].

Figures 9 and 10 show, at different scales, the fracture interface after flexural testing. The presence of the different mask layers is clearly visible in the interface (Fig. 9). These layers create a microcrack bridging action in the tensile region of the samples, therefore increasing flexural strength. The addition of the mask pieces also has a great influence on the nature of the failure, which is no longer brutal. In fact, when breaking, the fibres prevent the separation of two sections of the fibre-reinforced mortar sample which remain attached to one another (Fig. 11).

It is noted that the amount and nature of the fibres present in the interface, as well as their orientations, vary from one sample to another, even for samples of the same composition. This explains the variation in the resistance measurements obtained and the relatively large standard deviation.

The optical microscopic analysis in Fig. 10 shows that in general, the cementitious matrix has not been able to penetrate the inner and middle layers of the mask. This limits the fibre-matrix adhesion on the one hand and increases the porosity of the mortar on the other hand.

Thermal

Figure 12 shows the average thermal conductivity values measured for the different formulations.

As expected, the addition of the mask pieces causes a decrease in thermal conductivity. The decrease reaches up to 15% for the large pieces and 23% for the small pieces. This decrease can be attributed to the voids introduced by the masks inside the cementitious matrix.

It is also noted that the reduction is linear with respect to the amount of mask in the mortar.

Table 4 Flexural strength at 28 days (MPa)

Mask pieces quantity (%)	4 cm ² mask pieces		2 cm ² mask pieces	
	Av	S.D	Av	S.D
0	1.37	0.07	1.37	0.07
1	1.82	0.24	1.35	0.13
2	1.80	0.10	1.59	0.17
3	1.54	0.04	1.51	0.17
5	1.75	0.13	1.63	0.06

Fig. 9 Fracture interface after flexural tests: mortar with different layer mask

Fig. 10 Microscopic analysis of the fracture interface after flexural tests

Acoustics

Figure 13 shows the sound absorption coefficient for the different amounts of mask pieces.

In the figure, the data shown in dotted lines are those of the sound absorption coefficient for mask parts with dimensions $2\text{ cm} \times 2\text{ cm}$, and the data shown in solid line are for mask parts with dimensions $2\text{ cm} \times 1\text{ cm}$ ("L" in the name

(a) Ordinary mortar (M0)

(b) Mortar with pieces of mask (M2)

Fig. 11 Flexural tests

Fig. 12 Thermal conductivity

of the mixture denotes "large" dimension and "S" denotes small dimension).

It is noticed that the mortar without fibre is almost totally reflective for all frequencies with an absorption coefficient value that varies between 0.01 and 0.03. The value of the absorption coefficient as a function of frequency is constant.

However, with the addition of the mask pieces in the mortar, the sound absorption value increases for all frequencies. The maximum value occurred at 2 kHz. As the amount of mask pieces increases, the sound absorption value increases. The maximum value which was initially equal to 0.03 reaches the value of 0.32 for the dosage of 5% of small pieces of mask and 0.29 for the large pieces.

Capillary water absorption test

Figure 14 shows the height of the capillary rise in the samples. In general, the absorption of water by the samples

Fig. 13 Thermal conductivity

goes through two phases. From the beginning of the test until 8 h, the capillary rise in the samples with mask is higher than in the reference mortar. But after 8 h, the speed of the rise decreases, and this decrease is greater as the quantity of mask is greater. Moreover, after 8 h from the beginning of the test, the capillary rise becomes constant for the samples with 3% and 5% masks. It is also noticed that the capillary rise in the samples with small pieces of masks is lower than in the samples with large pieces, this is related to the size of the space reserved by the pieces of masks in the mortar. Indeed, as capillary absorption is a property related to the intercommunication of the internal pores in the reference mortar, larger pieces of mask favour a greater capillary flow of water.

Fig. 14 Capillary rise in the samples

Figure 15 shows the effect of the mask pieces on the capillary absorption of the mortars. It is found that the mortar containing small pieces of mask absorbs more than the reference mortar. However, this is only observed for 2 and 5% with large pieces of mask.

Based on the capillary absorption measurements (expressed as the weight of the absorbed water/unit inflow area) and using the Hall model, suggested by Wirquin et al. [28] for mortars, it is possible to calculate the sorptivities of the different mixtures. The results are summarised in Table 2.

$$W = A + S \text{ racine}(t) - C t \quad (1)$$

where W is the amount of the absorbed water/unit inflow area, S is the sorptivity of the sample, t the time, and A and C are constants.

The results, presented in Table 5, clearly show the good correlation obtained.

The largest increase in sorptivity is 50.5% obtained for 5% of large mask piece. The variation in sorptivity is significant and there is even a decrease compared to the reference mortar where 3% of large mask piece is added.

Fig. 15 Coefficient of capillary absorption of the samples

Table 5 Sorptivity of the samples

	A	C	S	ΔS	R^2
M0	0.95	0.1719	2.6698	–	0.9974
M1L	0.4886	0.2148	3.1252	0.4554	0.9972
M2L	0.5577	0.0634	2.8943	0.2245	0.9982
M3L	0.6827	0.1191	2.3758	–0.294	0.9996
M5L	0.2319	0.5322	5.3924	2.7226	0.9966
M1S	0.5789	0.4959	5.3202	2.6504	0.9638
M2S	2.126	0.1587	2.5013	–0.1685	0.9965
M3S	1.6308	0.1432	2.677	0.0072	0.9961
M5S	0.6947	0.5368	4.5661	1.8963	0.9963

The amount of the absorbed water increases since the presence of mask pieces creates additional capillaries due to their porosity. However, although in most cases the presence of mask pieces increases the sorptivity of the mortar, this is not associated with a higher capillary rise as already shown.

Conclusion

The purpose of this study is to valorise single-use mask waste, which has increased dramatically during the COVID 19 pandemic, in mortars. This is in order to solve the environmental pollution problems on the one hand and to improve the physical and mechanical characteristics on the other hand. The significant results of this study are as follows:

The compressive strength of the samples increases by up to 20% with the increase in the amount of mask pieces. The flexural strength increases by up to 30%. However, this increase is not uniform, since the mask consists of three different layers and the ratio representing each type of layer varies arbitrarily in the samples.

The addition of the mask pieces to the mortar also increased the sound absorption value for all frequencies. Thus, the maximum value that was initially equal to 0.03 for the reference mortar reaches the value of 0.32 for a dosage of 5% of small pieces. On the other hand, it is noticed through the capillarity test that the sorptivity of the mortar has increased by up to 50%, although this sorptivity is not accompanied by an increase in the final capillary rise.

Finally, it can be concluded that the use of mask pieces in mortars can bring two major benefits; the first is the resolution of an environmental problem, and the second is the improvement of a number of mortar characteristics.

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Declarations

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

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

- Kilmartin-Lynch S et al (2021) Preliminary evaluation of the feasibility of using polypropylene fibres from COVID-19 single-use face masks to improve the mechanical properties of concrete. *J Clean Prod* 296:126460
- Nzediegwu C, Chang SX (2020) Improper solid waste management increases potential for COVID-19 spread in developing countries. *Resour Conserv Recycl* 161:104947
- Sangkham S (2020) Face mask and medical waste disposal during the novel COVID-19 pandemic in Asia. *Case Stud Chem Environ Eng* 2:100052
- Saberian M, Li J, Kilmartin-Lynch S, Boroujeni M (2021) Repurposing of COVID-19 single-use face masks for pavements base/subbase. *Sci Total Environ* 769:145527
- Abbasi SA, Khalil AB, Arslan M (2020) Extensive use of face masks during COVID-19 pandemic:(micro-) plastic pollution and potential health concerns in the Arabian Peninsula. *Saudi J Biol Sci* 27(12):3181–3186
- Aragaw TA (2020) Surgical face masks as a potential source for microplastic pollution in the COVID-19 scenario. *Mar Pollut Bull* 159:111517
- Fadare OO, Okoffo ED (2020) Covid-19 face masks: a potential source of microplastic fibers in the environment. *Sci Total Environ* 737:140279
- Selvaranjan K et al (2021) Environmental challenges induced by extensive use of face masks during COVID-19: a review and potential solutions. *Environmental Challenges* 3:100039
- Ahmed HU et al (2021) Use of recycled fibers in concrete composites: a systematic comprehensive review. *Compos Part B Eng* 215:108769
- Faraj RH et al (2020) Use of recycled plastic in self-compacting concrete: a comprehensive review on fresh and mechanical properties. *J Build Eng* 30:101283
- Faraj RH, Sherwani AFH, Daraei A (2019) Mechanical, fracture and durability properties of self-compacting high strength concrete containing recycled polypropylene plastic particles. *J Build Eng* 25:100808
- Kakooei S et al (2012) The effects of polypropylene fibers on the properties of reinforced concrete structures. *Constr Build Mater* 27(1):73–77
- Malek M et al (2020) Characteristics of recycled polypropylene fibers as an addition to concrete fabrication based on portland cement. *Materials* 13(8):1827
- Madhavi TC, Raju LS, Mathur D (2014) Polypropylene fiber reinforced concrete-a review. *Int J Emerg Technol Adv Eng* 4(4):114–118
- Chowdhury H, Chowdhury T, Sait SM (2021) Estimating marine plastic pollution from COVID-19 face masks in coastal regions. *Mar Pollut Bull* 168:112419
- Standard EN 12390-2: 2012 (2012) Testing hardened concrete—part 2: making and curing specimens for strength tests
- NF EN 196-1 (2006) Méthodes d'essais des ciments-Partie 1: détermination des résistances mécaniques [Methods of testing cements—part 1: determination of mechanical strengths]
- NF EN 13057 (2002) Indice de classement : P 18-945. Produits et systèmes pour la protection et la réparation des structures en béton. Méthodes d'essai. Détermination de l'absorption capillaire. Association Française de Normalisation (AFNOR)
- Savado N et al (2015) Durability of composite cement with Tefereyre (NIGER) coal bottom ash: capillary absorption, porosity to water and acid attack. *J Mater Eng Struct* 2(4):213–223
- ASTM. Standard C518-91 (1991) Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the heat flow meter apparatus. vol 4.06
- ISO (1991) SO 8301:1991 Thermal insulation—determination of steady-state thermal resistance and related properties—heat flow meter apparatus. ISO, Switzerland
- Standard test method for impedance and absorption of acoustical materials using a tube, two microphones and a digital frequency analysis system. ASTM E-1050-08 (2008). ASTM International, West Conshohocken, PA, USA
- International Organization for Standardization (1998) 10534-2: 1998 (E), Acoustics—determination of sound absorption coefficient and impedance in impedance tubes—part 2: transfer function method. International Organization for Standardization (1998)
- Al-Hadithi AI, Noaman AT, Mosleh WK (2019) Mechanical properties and impact behavior of PET fiber reinforced self-compacting concrete (SCC). *Compos Struct* 224:111021
- Hama SM, Hilal NN (2017) Fresh properties of self-compacting concrete with plastic waste as partial replacement of sand. *Int J Sustain Built Environ* 6(2):299–308
- Mohammed AA, Rahim AAF (2020) Experimental behavior and analysis of high strength concrete beams reinforced with PET waste fiber. *Constr Build Mater* 244:118350
- Patel PA, Desai AK, Desai JA (2012) Evaluation of engineering properties for polypropylene fibre reinforced concrete. *Int J Adv Eng Technol* 3(1):42–45
- Wirquin E, Hadjieva-Zaharieva R, Buyle-Bodin F (2000) Use of water absorption by concrete as a criterion of the durability of concrete-application to recycled aggregated concrete. *Mater Struct* 33(6):403–408