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Development of Building and Insulation Epoxy Based Composite Materials Loaded with Construction and Demolition Wastes; Mechanical and Thermal- Insulation Behaviour Analysis

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Authors' contributions

This work was carried out in collaboration between both authors. Author LZ designed the study. Author CB performed the experimental analysis, managed the literature review, wrote the first draft of the manuscript and managed the analyses of the study. Both authors read and approved the final manuscript.

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ABSTRACT

The development of composite materials filled using Construction and Demolition wastes (CDW), characterised by descent mechanical and thermo-insulating properties has been investigated experimentally in this paper. Composites of epoxy resin containing CDW of different grain size and w/w concentrations as additives were manufactured. Additives used, have been prepared through appropriate processing. Our investigations indicated that flexural and shear properties of composites encapsulating 300 μm additives at 30% w/w have been improved, compared to all other composites examined (i.e. composites loaded with 300 μm additives at 40% and 50% (w/w), 500 μm loaded composites at 30%, 40, and 50% w/w), taking a value of 60.03 MPa for flexural strength and 7.54 MPa for shear strength respectively, characterizing them as optimum, in terms of mechanical performance. Next, the thermal insulation capacity study for these materials has been then carried out. Thermo-insulating efficiency of composites has been evaluated by determination

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of thermal conductivity coefficient (λ), which has been calculated at 1.02 W m^{-1} K^{-1}, exhibiting good insulation performance, compared to conventional building and insulation materials. The feature of these materials to demonstrate combined adequate mechanical and thermal insulation properties, confirms their appropriateness to be utilised as building and insulation materials.

Keywords: Composite materials; CDW additives; mechanical properties; thermal insulation; epoxy resin.

ABBREVIATIONS

CDW : Construction and Demolition waste
EU : European Union

1. INTRODUCTION

Construction and demolition wastes (CDW) account for about 30% of the total amount of waste generated in the European Union (EU) and are characterised as one of the most difficult waste streams in terms of management [1]. Activities of the construction sector and particularly building or infrastructure projects, demolitions and renovations, road network planning and maintenance are considered as generating sources of these wastes [2].

CDW mainly consist of aggregate materials such as concrete, bricks, soils, stones and other materials (plastics, glass, metals, wood), which can be recovered through recycling [3].

Integrated management strategies that could maximise CDW recovery efficiency were suggested by researches [4-12]. Sustainability issues related to CDW management were also considered in many research studies [13,14]. Alternative exploitation options of specific CDW fractions (concrete, ceramics etc) in infrastructure projects, substituting raw materials [15-18] or concrete production [19-21] were also investigated.

Despite the extended research carried out, the most common CDW management practices applied in many countries throughout the globe are landfilling and illegal dumping (fly tipping) [3].

According to data referred in past research papers, about 140 million tons of CDW are generated annually in USA, out of which over 70% is landfilled [2,22]. The situation is even worse in Eastern countries, with landfilled CDW ranging between 90-95% of the total CDW production [23-26].

At EU level, the enactment of Directive 2008/98/EC enforced member-countries to achieve a minimum target 70% (by weight) of non-hazardous CDW as far as re-use, recycling or recovery is concerned by 2020 [27,28]. As a consequence of the strictness of this legislative framework, only five out of the 27 EU countries have managed to achieve recycling rates that meet its demands [29].

The outstanding properties of composite materials resulted to their extensive use in many applications, such as aircraft industry, building and construction applications, medical and biomedical equipment, automotive and motorsports industry, electrical equipment manufacturing, during the last 40-50 years [30-36]. This along with emerging waste management issues led researchers to investigate the potentials arising through wastes (mainly agricultural and industrial) utilisation as filling additives in different types of polymer composite materials [37-41].

This study aims to investigate potentials arising from the development of new composite materials filled using CDW additives characterised by good mechanical and thermal insulating properties, and can be used as substitutes of conventional materials in construction applications. On the other hand, considering the environmental benefits arising from the suggested CDW exploitation option in terms of minimising raw materials extraction demands and CDW disposal by landfilling or illegal dumping, are significant.

2. MATERIALS AND METHODS

2.1 Additive Material-Resin System (Matrix)

Mixed wastes generated from demolition and renovation projects, were collected from building demolition sites. These wastes mainly consisted of various flooring wastes (tiles, marbles etc), window glazing, wood, soils, building materials (bricks, plasters, concrete etc) and other recoverable materials (plastics, metals, glass).

The epoxy resin selected and used as matrix in composites' manufacture was Epoxol 2874. This resin is a product of Neotex Co, and has been purchased as a complete system (resin and hardener) from the market, at 15.00 €/kg.

2.2 Additive Material Processing and Production

Additives of two different granular sizes, 300 μm and 500 μm respectively in powder form, have been produced from appropriate processing of collected CDW. The procedure used to produce the required additive fillers is presented in Fig. 1.

2.3 Environmental Benefits of CDW Recycling

The benefits resulting through the implementation of the introduced management option was presented. In particular, a brief analysis of the energy consumed for the manufacture of CDW filling additives was carried out. The resulting reduction in resources demand (energy, raw materials, landfill space) has been evaluated.

2.4 Investigation of Mechanical Properties of CDW Filled Epoxy Composites

The required proportions of epoxy resin Epoxol 2874, hardener (≈ 3 parts of epoxy : 2 parts of hardener) and CDW additives have been weighed using an electronic weighing machine. The three ingredients were afterwards placed in a pot and continuously stirred for 5-6 minutes till (macroscopic) homogenization. Epoxy composites containing CDW additives of 300 μm and 500 μm under loading quantities of 30%, 40%, and 50% (w/w) have been prepared. The blend produced after stirring has been appropriately moulded, using hand lay-up

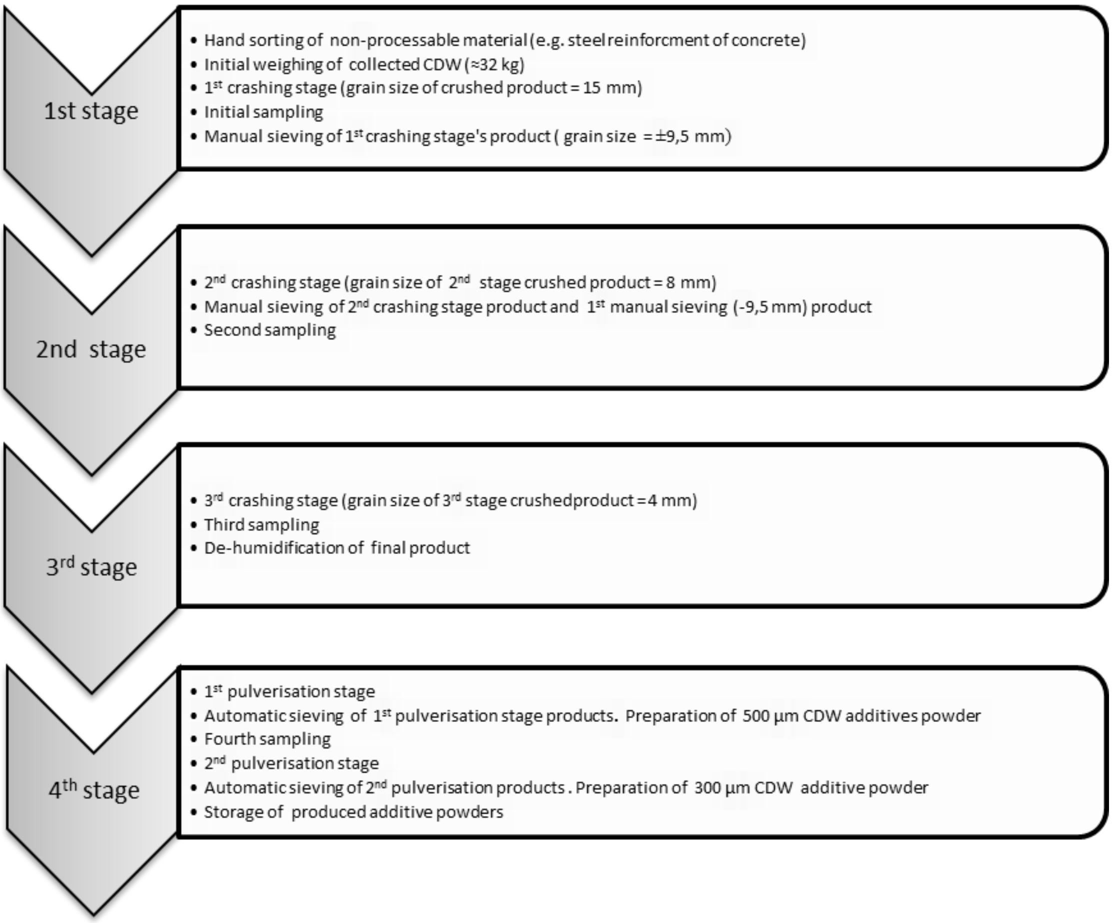

Fig. 1. Production process of CDW additives

method for flexural and shear strength tests according to the standards and thermally cured at 60ºC for 6 hours. Mold's surfaces have been treated with wax to allow easier detachment of composites after curing. Flexural and shear strength characteristics, have been studied according to ASTM D 790 (flexural strength) and ASTM D 2344 (shear strength) using a three-point bending apparatus (Fig. 2) and specimens with dimensions 21 x 1.0 x 0.3 cm for flexural strength and 21 x 1.7 x 0.3 cm for shear strength measurements respectively (Fig. 3). Flexural strength has been measured after setting the span between the sample holders at 10 cm and shear strength for span distance setting at 1 cm. Five specimens of each composite have been tested. Mechanical performance of composites has been determined, as the average of recorded flexural and shear strength values. Results of every composites' batch were almost identical.

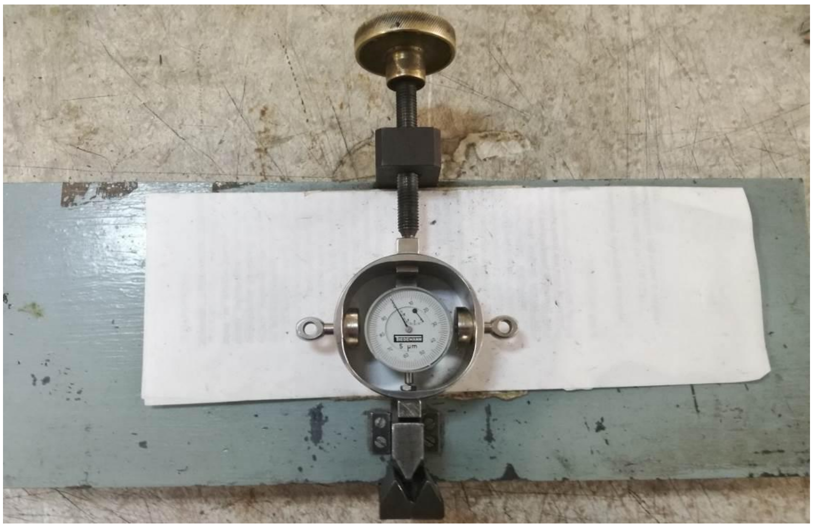

Fig. 2. Three-point bending test machine

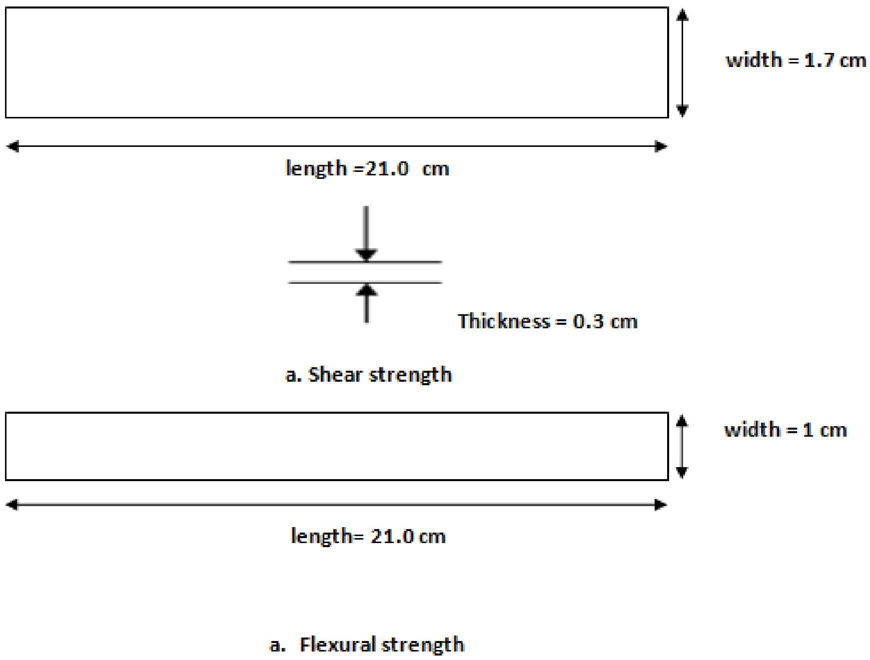

Fig. 3. Dimensions of specimens

2.5 Thermal Insulation Capacity of CDW Filled Epoxy Composites

Under similar ingredient proportions as those used in the manufacturing of composites that demonstrated optimum flexural and shear properties as described in the following sections (Results and Discussion, Figs. 6 and 7) proper composite specimens have been manufactured. After continuous stirring the resulting blend of epoxy, hardener and CDW additives, has been poured into a baking tray and thermally cured at 60°C for 4 hours. Moulding tray's surfaces were again treated with wax to prevent specimens from been damaged during de-moulding. The thermo-insulating capacity of composite materials has been evaluated using a laboratory manufactured Guarded-Hot-Plate apparatus (Fig. 4) that operates according to ASTM C177. The two slots in between the cooling plates and heating source of the apparatus contained the composites to be tested. To minimise system's heat loss in order to avoid false measurement results, the whole assembly (specimens, heating source, cooling components) was appropriately insulated as shown in Fig. 5. Thermal

Fig. 4. Thermal conductivity measuring equipment

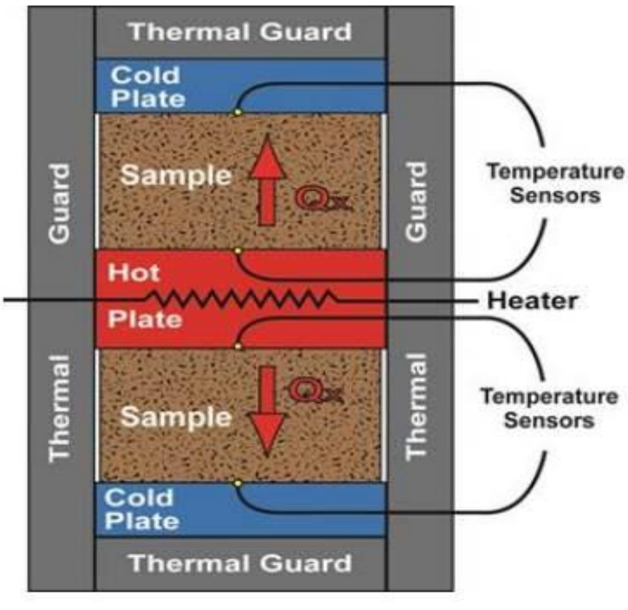

Fig. 5. Sectional view of insulated system

conductivity coefficient λ has been evaluated through solving Equation 2,

$$\lambda = \frac{\Phi * S_m}{2A(\Theta_{wm} - \Theta_{cm})} \quad (2)$$

where:

Φ: Capacity resistance of heating surface,
S_m: Composites' average thickness (cm),
A: Composites' average surface area (cm^2),
Θ_{wm}: Composites' warm surfaces av. Temp. ($^\circ$K),
Θ_{cm}: Composites' cold surfaces av. Temp. ($^\circ$K).

All required parameters involved have been calculated according to the literature and the error in measurements of thermal conductivity's coefficient, λ, was ±5% [42].

3. RESULTS AND DISCUSSION

3.1 Flexural Strength

Flexural strength results of manufactured composites are presented in Fig. 6, where pure epoxy specimens are coloured in orange and composites incorporating 300 μm 500 μm CDW additives are represented in blue and red colour respectively.

Particularly, flexural strength of composites has been reduced by 64% (300 μm) and 79.3% (500 μm) once the w/w concentration of additive content in composites has been increased from 0% to 30% w/w, in comparison to pure epoxy materials.

Increasing additives w/w percentage to 40%, led to the decrease of flexural strength by 26.5% (500 μm) and 33.9% (300 μm) compared to composites filled with additives at 30% (w/w). Further increase of additive concentration to 50% (w/w) resulted in even greater decrease of flexural strength values by 4% (500 μm CDW filled composites) and 33.3% (300 μm CDW filled composites) in comparison to composites loaded at a concentration of 40% w/w.

Mechanical behaviour of composite materials has been affected once additives of different grain size have been used as fillers.

Analytically, composites containing 30% (w/w) of additives, presented a decrease of 42.3% in flexural strength once 500 μm CDW additives have been used (as filler) instead of 300 μm. Similarly, composites manufactured including additives at concentrations of 40% and 50% (w/w) were characterized by inferior flexural properties. Flexural strength was reduced by 35.9% and 7.7% while larger grain size filler has been added in the composites. All measurements carried out in order to determine flexural strength, involved an error of ±7%.

3.2 Shear Strength

Fig. 7 shows the shear strength results properties of CDW loaded epoxy composites. In a similar manner as described for bending strength, pure epoxy materials are shown represented in orange coloured column and 300 μm and 500 μm loaded composites are represented in blue and red columns respectively.

As a result of CDW additives encapsulation at 30% w/w, the shear strength has been decreased by 45.4% for composites manufactured using 300 μm and by 73% for composites using 500 μm CDW additives respectively, compared to pure epoxy resin materials.

Increasing the w/w quantity of filling additives to 40%, led to further decrease of shear strength by 52.6% for composites manufactured using 500 μm particulate fillers and by 8.1% for composites of 300 μm particulate fillers respectively, in comparison to composites loaded under 30% w/w.

Further increase of encapsulated filler's to 50% brought upon a greater shear strength reduction which reached 40.1% for composites contained 500 μm additives and approximately 26% for composites containing 300 μm additives compared to the ones loaded at concentration of 40% w/w.

Granular sizing of CDW fillers is again of significant importance. In particular, addition of 500 μm additives in substitution of 300 μm led to the reduction of shear strength by 50.6%, 4.2% and 22.9% for composites containing 30%, 40% and 50% w/w additives respectively. The error involved in shear strength measurements, was ±7%.

3.3 Thermal Insulation Efficiency of CDW Loaded Composites

Thermo-insulating efficiency of manufactured composites has been evaluated by determination of the thermal conductivity coefficient, λ. As shown in Table 1, λ for CDW loaded composites has been calculated at 1.02 W m^{-1} K^{-1}, validating that these materials demonstrate relatively good thermoinsulating properties, in comparison to common building materials referred in the literature [43]. Additionally, thermo-insulating capacity of CDW filled composites has been improved by 15 % in comparison to pure epoxy materials.

Apart from that, the addition of CDW particulate fillers in the epoxy matrix enabled the manufacture of composite materials characterised by adequate mechanical properties and thermal insulation efficiency.

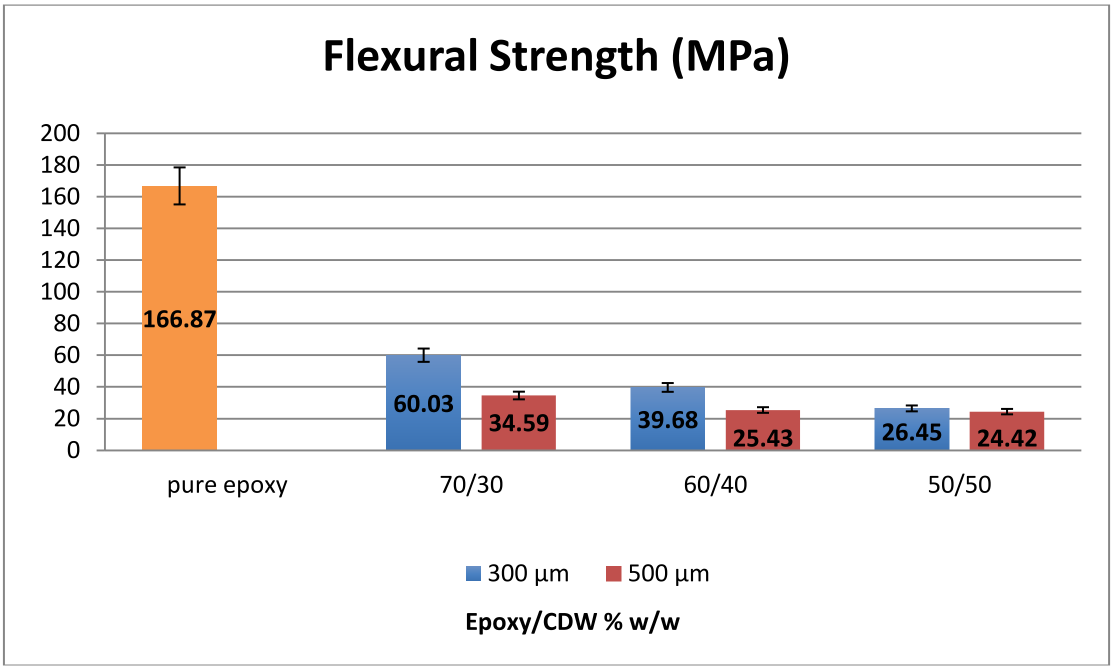

Fig. 6. Flexural strength results of CDW filled epoxy composites

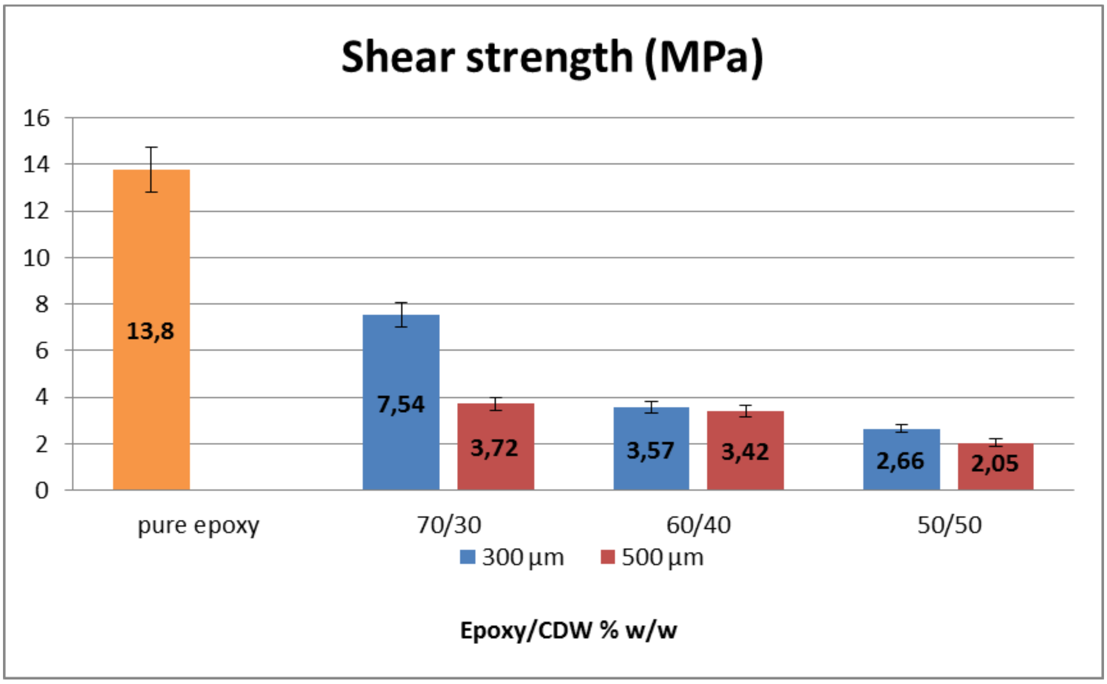

Fig. 7. Shear strength results of CDW filled epoxy composites

Table 1. Thermal conductivity of epoxy composites manufactured using additives of CDW versus other insulating materials

Material	Polymer matrix epoxy (% w/w)	Additive (filler) CDW (% w/w)	Coefficient of thermal conductivity, λ (W $m^{-1}K^{-1}$)
300 μm CDW additives epoxy composite (experimentally determined)	70	30	1.02
Pure epoxy resin (experimentally determined)	100	0	1.2
Brick	-	-	1.32
Concrete block (cinder)	-	-	0.9-1.35
Cement plaster	-	-	0.7-1.50

Table 2. Energy demands of CDW preparation and composites manufacture

Materials and energy	Output power (kW)	Energy consumption (Kwh/kg)	Total energy consumption in MJ/kg
Jaw crusher	3	0.04	-
Automatic sieve	0.18	0.005	-
Drying oven	1.6	1.2	-
Autoclave (composites forming)	0.5	0.1	-
Total	**5.28**	**1.345**	**4.71**

3.4 Sustainability Analysis

Table 2 presents the energy consumption demands per kg of processed CDW additive. In particular, the energy required to produce CDW filled epoxy composite materials has been calculated at 1.345 kWh/kg. This is significantly smaller compared to energy consumed for extracting of 1 kg of raw materials considering that there are various secondary factors that dramatically increase the total resources consumption [44]. The total energy consumed during composites' manufacture, has been estimated at 4.71 MJ/kg. This value is significantly lower compared to energy consumed in manufacturing of insulation materials [45]. Considering that around 850 million tons of CDW is generated in annual basis in the EU [46] and the raw materials annual extraction in order to cover the needs of construction sector is estimated to be the triple of this quantity according to the literature [47], the economic and environmental benefits arising from this specific CDW exploitation option are huge. Analytically, raw materials production costs can be neglected, since CDW are used as their substitutes. Apart from that, the resulting environmental burden as far as resource consumption is concerned (virgin materials extraction, space availability for waste disposal etc) is minimised.

4. CONCLUSIONS

We investigated the effects of CDW addition in mechanical and thermal insulation properties of epoxy matrix composite materials. Composites containing 30% (w/w) of 300 μm CDW additives were the optimum among manufactured composites, demonstrating sufficient flexural and shear strength characteristics. As a result of CDW loading, composites' thermo-insulating capacity demonstrated an enhancement of 15% in the coefficient of thermal conductivity, λ. Besides the environmental benefits arising from the specific CDW recovery option, the adequately good thermo-insulating and mechanical characteristics of these materials outline their appropriateness to be used as building and insulation materials.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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