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Recycling and Exploitation of Construction and Demolition Wastes as Additives in Unsaturated Polyester Composite Building and Insulation Materials; Mechanical and Thermal Properties Investigation

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Authors' contributions

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

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ABSTRACT

This research investigates the potential of manufacturing composite materials combining good mechanical and thermal insulation characteristics using C&D wastes (Construction and Demolition waste) in substitution of raw aggregates. Unsaturated polyester matrix composites encapsulating C&D waste of 300 μm and 500 μm as additives, at concentrations of 30%, 40% and 50 (% w/w) respectively, were manufactured. The effects of loading these materials with C&D wastes, in terms of mechanical and thermo-insulating performance were studied. Experimental research revealed the strong interrelation between the mechanical performance of materials and parameters such as grain size and concentration of loading agent. In particular, composites encapsulating 300 μm

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additives demonstrated improved flexural and shear properties, taking values of 34.59 MPa (30% additives), 35.61 MPa (40% additives) and 30.25 MPa (50% additives) for flexural strength and 3.72 MPa (30% additives), 4.18 MPa (40% additives) and 2.66 MPa (50% additives) for shear strength, compared to corresponding 500 μm loaded composites which flexural strength reached 33.58 MPa (30% additives), 34.6 MPa (40% additives) and 27.47 MPa (50% additives). Similarly shear strength reached 2.81 MPa (30% additives), 3.87 MPa (40% additives) and 2.5 MPa (50% additives) respectively. Composite materials loaded at a concentration of 40% (w/w) using 300 μm C&D waste additives, exhibited optimal mechanical efficiency in terms of flexural and shear strength. Thermo-insulating properties of optimum, in terms of mechanical behavior, composite materials were afterwards investigated. Thermal insulation efficiency was determined by measurement of thermal conductivity coefficient (λ) which was calculated at 0.39 W m^{-1} K^{-1}, demonstrating good insulating properties compared to common insulation materials In conclusion, the characteristic attribute of these materials to exhibit adequate mechanical and thermal insulation properties, as validated by the experimental results, indicates their suitability as building and insulation materials in construction applications.

Keywords: Composite materials; construction and demolition waste; additives; mechanical properties, thermal properties; insulation; unsaturated polyester.

ABBREVIATIONS

C&D waste : Construction and Demolition waste
EU : European Union
MEKP : Methyl-ethyl-ketone peroxide

1. INTRODUCTION

Civil infrastructure projects and building construction sectors consume over half of the material and energy resources [1]. The irrational consumption model of these activities designated them as the most inefficient “consumers” [2], outlining at the same time, the importance of implementing more sustainable strategies in every distinct level of materials production and life-cycle [3-10]. Moreover, recycling and recovery issues related to construction and demolition waste (C&D waste) management, have become crucial and discussed in many research studies [11-16].

Even though strict environmental standards and a demanding legislative framework are in force within the European Union (EU), setting incredibly high quantitative recycling targets as far as C&D waste management is concerned, the average recycling percentage rates in EU member countries hardly reaches 50% [17-31].

During the last decades, composite materials are being widely used in a great number of applications as a result of the outstanding mechanical properties they exhibit [32-41]. The need to reduce production costs and keep at the same time materials' properties in adequately descent levels designated the positive effects of various kinds of particulate fillers addition in composite materials [42-51]. According to sustainability standards and as far as environmental awareness increased, many researchers investigated the possibility of utilising various wastes or by-products, as additives in composite materials manufacturing [52-61]. However, the possibility of exploiting C&D wastes as raw materials in manufacturing cheap building materials which are environmental friendly and present decent properties, have not been researched yet in great extent. Research papers concerned with the issues involved in C&D waste recycling are concentrated on an investigation of specific C&D wastes in concrete [63,64], rural roads [65,66] and mortars construction [67,68].

The aim of this research is to develop new C&D waste loaded composite materials combining appropriate mechanical and thermal insulating properties, enabling them to be used as building and insulation materials. Besides that, a different exploiting potential for C&D waste is introduced.

2. MATERIALS AND METHODS

2.1 Raw Materials and Resin System

Construction and Demolition waste containing various materials such as bricks, cinder blocks, gravel, tiles, soil, glass, concrete, wall coating (plaster), produced from demolished buildings, was collected from a specialised C&D waste processing facility where they have been guided for further management. Composition of waste was determined by means of visual inspection.

The resin used as a matrix for composites was unsaturated thixotropic polyester PE6/TC system of Neotex Co., which is available in the market as a complete set (resin and curing agent).

2.2 Preparation of Additive Substance from C&D Waste

After removing contaminants which could not be processed (such as steel reinforcement parts), by means of hand-sorting and initial weighing of collected waste, consecutive stages of sampling through laboratory splitter to ensure sample's maximal homogeneity, were performed. Crushing in a jaw-crusher took place afterwards to bring C&D waste in a more manageable size and enable further processing. The initial crushing product was placed for 24 hours in the oven to remove contained moisture. After de-humidification, a sequence of sieving routines, were executed. Additional splitting-sampling steps took place and powders of two granulometric sizes, 300 μm and 500 μm, were finally prepared through grinding in a pulverising mill.

2.3 CDW-loaded Polyester Composites' Mechanical Behaviour Analysis

Mixture of unsaturated thixotropic polyester PE 6/TC adding the appropriate quantity (≈3% w/w) of curing agent, Methyl-ethyl-ketone peroxide (MEKP) and loaded with C&D waste additives of granular size 300 μm and 500 μm at concentrations of 30%, 40%, and 50% (w/w) respectively, were prepared after continuous stirring the ingredients in a pot for 5 minutes. Weight measurements required were performed using an electronic weighing machine. Final mixture was carefully poured into a mould suitable for flexural and shear strength according to the standards. A thin layer of wax was applied on mould's surfaces to enable easy and undamaged removal of specimens. The mould containing the poured mixture was placed in a laboratory oven and thermally cured at 60°C for 20 minutes. Flexural and shear tests of unsaturated polyester C&D waste loaded composites, were conducted according to the three-point method by ASTM D 790 [69] and ASTM D 2344 [70] (see Fig.1). The distance between the supporting basis of three-point bending test machine was set at 10 cm for flexural strength measurements and 1 cm for shear strength measurements respectively.

2.4 CDW-loaded Polyester Composites' Thermal Insulation Properties

Thermo-insulating properties of composites were defined by determination of thermal conductivity coefficient, λ, using Eq. 1

$$\lambda = \frac{\Phi * S_m}{2A(\Theta_{wm} - \Theta_{cm})} \tag{1}$$

Where;

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

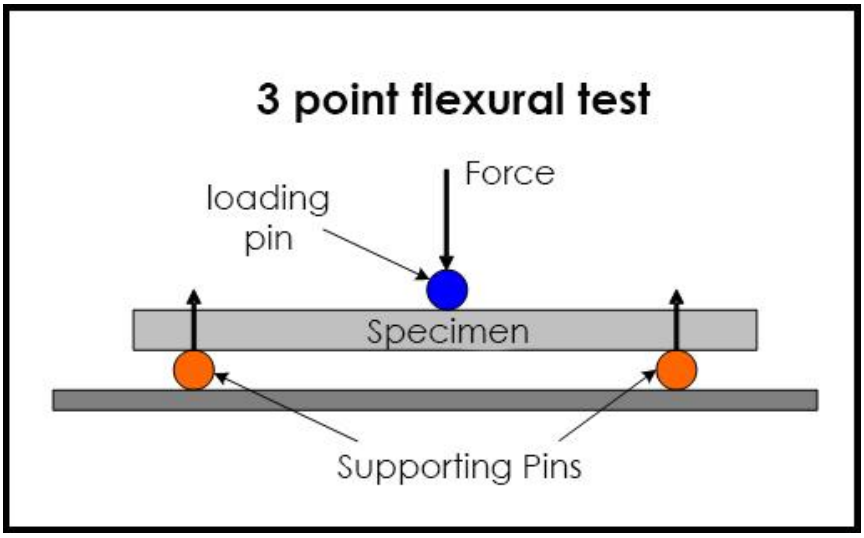

Fig. 1. Schematic of the three-point test

Fig. 2. Thermal conductivity measurement apparatus

Experimental measurement of composites thermal insulation efficiency was carried out by means of a guarded-hot-plate apparatus [71-73] according to ASTM C177 [74]. The set-up of the apparatus used is presented in Fig. 2.

Discoid composite specimens with identical dimensions to those of heating and cooling components of the experimental set-up were prepared. Materials to be tested were manufactured following the same procedure, based on composition characteristics of optimum (in terms of mechanical behaviour) composites, as far as polyester/ curing agent proportions, additives grain size and w/w concentration is concerned (see Fig. 3 and Fig. 4, section 3.1). After mixing, the final blend was poured in a tray and cured in the oven at 60°C for 20 min. Wax was again applied to ease composites removal from the moulding tray. Specimens to be tested were placed in the spaces between the heater and the two cooling plates of the hot-guarded-plate. The experimental set-up (heater, cooling plates, and test specimens) after being assembled was appropriately insulated.

Error involved in measurements of thermal conductivity's coefficient, λ, is ±5%. Required calculations were performed according to the literature [75].

3. RESULTS AND DISCUSSION

3.1 C&D Waste Particle-Filled Polyester Composites

3.1.1 Flexural strength

Flexural strength of composites under investigation is presented in Fig. 3. Pure polyester materials are represented in light green coloured column, 300 μm and 500 μm C&D waste loaded composites are represented in blue and orange coloured columns respectively. Composites incorporating 30% w/w additives, demonstrated a decrease in flexural strength of 55.4% once 500 μm is used as filler and 54.1% in the case of 300 μm additive respectively, compared to flexural strength recorded for pure unsaturated polyester materials. Increasing filling agent's percentage to 40% acts on inversely. At this specific concentration of additive flexural strength of composites is improved by 2.95% (500 μm filler) and 2.86% (300 μm filler) in comparison to materials incorporating 30% of C&D waste additive. Further increase of filler's concentration from 40% to 50% leads to significant decrease of flexural strength about 20.6% for composites loaded with 500 μm powder and 15.1% for 300 μm loaded ones respectively, compared to those loaded with 40%

w/w additives. Adding filler of different grain size led to modifications in composites bending strength. In particular, composites filled with 30%, demonstrated a decrease of 2.92% in flexural strength once 500 μm filling powder is used, compared to these in which 300 μm filler is used. Similarly, composites loaded with 40% presented a decrease of 2.84% in flexural strength and composites encapsulated 50% C&D waste additive, demonstrated a reduction of 9.19% respectively. Optimum flexural strength values were presented by composites loaded with 40% w/w using 300 μm additives compared to all loading scenarios studied.

3.1.2 Shear strength

Fig. 4 presents shear strength of manufactured composites. As in the case of flexural strength graphical illustration, unloaded composites (pure polyester) are represented in light green coloured column and those filled with additives of 300 μm and 500 μm are represented in blue and orange coloured columns. Adding 30% w/w of filling agent in the polyester composites, led to the decrease of shear strength by 79.9% for composites incorporating 500 μm additives and 73.3% for those containing 300 μm additives respectively, compared to the shear strength values measured for pure polyester specimens (matrix). Increasing the concentration of filling agent to 40% had an inverse result, since shear strength composites was improved by 27.4% (500 μm filler) and 11% (300 μm filler) compared to those loaded at a concentration of 30% w/w. Further increase of loading concentration from 40% to 50% led to an even greater reduction of shear strength values about 35.4% (composites incorporating 500 μm additives) and 36.4% (composites with 300 μm additive), in comparison to 40% w/w loaded composites. An enhancement in shear strength was exhibited by composites encapsulating 300μm C&D waste additives at 40% w/w, in comparison to all other additive incorporating composites examined. Additive's granular magnitude is of great importance as far as shear strength is concerned. Analytically, encapsulation of additives at 30%, led to the reduction of shear strength by 24.5% while 500 μm filler is used in place of 300 μm. Correspondingly, composites containing additive at concentration of 40% presented a shear strength reduction of 7.42% and those containing 50% of filler demonstrated a downsizing of 6.01% respectively, once the 500 μm C&D waste additive was used to load composites, instead of 300 μm.

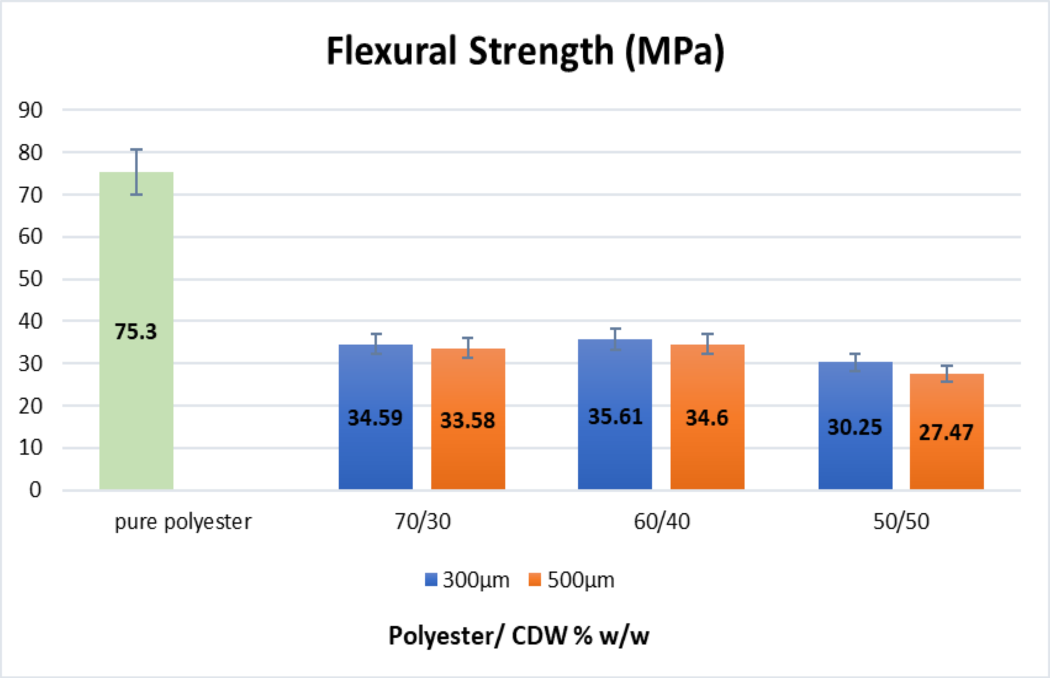

Fig. 3. CDW-filled composites' flexural strength
(Note: All Measurements include +/- 7% of error)

Table 1. C&D waste loaded polyester composites versus common insulation materials-Coefficients of thermal conductivity

Material	Polymer matrix Polyester/ MEKP (% w/w)	Additive (filler) CDW (% w/w)	Coefficient of thermal conductivity, λ (W $m^{-1}K^{-1}$)	Granular magnitude of filler (μm)
C&D waste-loaded composite*	60	40	0.39	300
Commercial Unsat. Polyester*	100	-	0.2664*	
Expanded Polystyrene (XPS)	100	-	0.029-0.041**	
Extruded polystyrene (EPS)	100	-	0.025-0.035**	
Polyurethane foam (PUR)	100	-	0.020 -0.027**	
Unsat. Commercial Polyester			0.24***	

** Experimentally determined*
*** Values found in literature*
**** Experimentally determined value of pure polyester found in the literature*

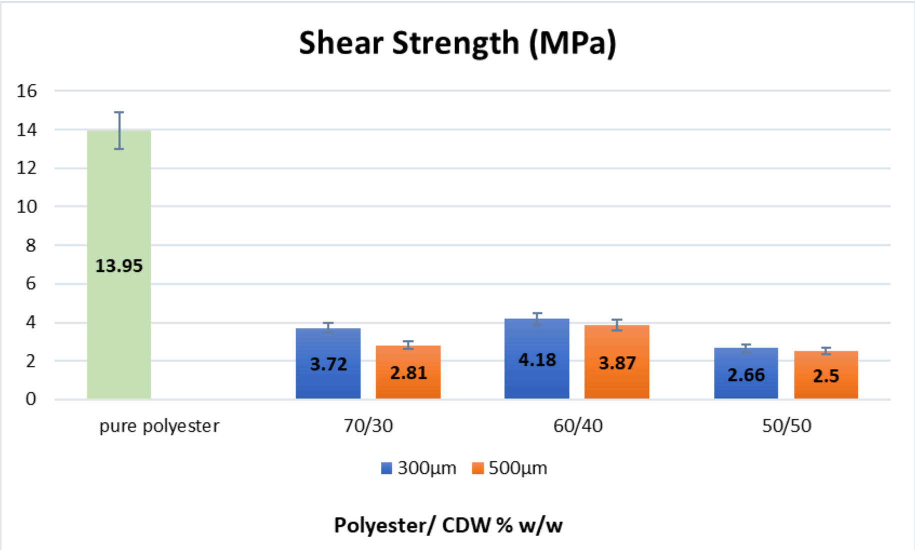

Fig. 4. CDW-filled composites' shear strength
(Note: All Measurements include +/- 7% of error)

3.2 Thermal Insulation Properties

The effects of loading on thermal insulation properties of composites were assessed by estimation of thermal conductivity coefficient, λ. Thermal conductivity coefficient took characteristic values which are presented in Table 1. Analytically, thermal conductivity coefficient of C&D waste loaded polyester composites was calculated at 0.39 W m-1 K-1. This value appears to be increased compared to corresponding λ values of polystyrene based (0.025-0.041 W m-1 K-1) and polyurethane foam (0.020-0.027 W m-1 K-1) materials that are widely used as insulators [76]. Thermo-insulating efficiency of composites was affected by C&D waste addition decreasing by 31% compared to the experimentally determined value obtained for pure polyester specimens. The measured thermal conductivity coefficient was almost identical in comparison to pure polyester λ values found in literature [77]. Encapsulation of C&D waste fillers led to manufacturing of materials with low thermal conductivity combining sufficiently good mechanical strength.

4. CONCLUSIONS

In the present study the effect of incorporating C&D wastes on polyester matrix in terms of mechanical performance and thermo-insulating efficiency of the resulting composites was studied. The optimum manufactured composites were those loaded with C&D wastes of 300μm at concentration of 40% (w/w), exhibiting adequately good mechanical performance. The thermo-insulating properties were slightly affected compared to the pure polyester, resulting in reduction of the thermal conductivity coefficient, λ. Those results along with the recycling of the wastes indicate that they are appropriate and can be utilized as building and insulation materials in construction applications.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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