# Effects of Construction and Demolition Wastes particle-loading on mechanical response of polymeric composite materials

C. Bogiatzidis[1, 2], L. Zoumpoulakis[1],

[1] National Technical University of Athens, School of Chemical Engineering, Department of Materials Science and Engineering, Athens, 15780, Greece
[2] Hellenic Recycling Agency, Department of Alternative Waste Management, Athens, 11251, Greece
Presenting author email: k.mpogiatzidis@eoan.gr

## Abstract

This paper focuses on the study of mechanical behavior of Polymeric Matrix Composites (PMCs') that incorporate recyclable Construction and Demolition Wastes (CDW) as filler.
CDW required were collected by a specialized Construction and Demolition Waste management facility.
Prior to experimental part of the study, CDW were passed through necessary processing stages (crushing, sieving, sampling, de-humidification, grinding). Two different micro-powders of CDW were produced (300 μm and 500 μm).
Performance of resin system chosen to form the matrix of PMCs' has been thoroughly and individually examined. Composites were made purely by epoxy resin, in varying mixture (resin/ curing substance) ratios and thermally processed for different time periods. PMCs' mechanical properties were experimentally examined and monitored.
Composite materials reinforced by CDW micro-particles addition at different (%w/w) concentrations have been fabricated and their behavioral response was investigated.
Experimental results confirm the strong interrelation between PMCs' mechanical properties and parameters, such as curing time, resin/ hardener mixture ratio, filling substance's concentration within the composites and filling material granular size.
Increasing concentration of filling CDW micro-particles had as result the downgrading of flexural and shear strength of CDW loaded composites in comparison to pure epoxy resin composites.

**Keywords:** Composite materials, CDW, mechanical properties, resins, micro-particles

## Introduction

Construction and demolition wastes (CDW) account for about 25% of the total amount of waste generated in the EU and considered to be among the heaviest and bulkier wastes [1]. As wastes, they consist mainly of concrete, iron, bricks, plasters, soils, stones and various other materials (plastics, glass, metals, wood), which can be re-exploited through recycling [2].

They are classified in the broader category of Demolition Construction Excavations wastes and can be placed under code 17 of the European Waste Catalogue [3].

Waste Framework Directive 2008/98/EC, (Article 11.2) enforced EU member-countries to achieve a minimum target 70% (by weight) of non-hazardous construction and demolition waste as far as re-use, recycling or recovery is concerned by 2020 [4, 5].

Nevertheless, achieved recycling rates show huge variations throughout member- countries of the European Union [1].

These differentiations reflect in a very representative manner, that management strategies adopted and implemented at EU level, have not yet performed as expected. Therefore, alternative methods have to be placed under consideration in order to boost the actual performance of alternative management of CDW and meet in parallel the demands of legislation.

The urge for environmental friendly materials has become nowadays more necessary than ever. Due to abusive consumption which resulted to the depletion of primary resources [6], sustainability and circular economy issues have emerged, leading to reconsideration of construction practices as well as CDW management plans and strategies, upon a wider and more integrated perspective [7, 8].

Considering sustainability and eco-efficiency potentials that can be achieved through CDW recycling in the composite materials industry, research has not yet demonstrated remarkable results. Some research studies have been published, concerning future trends and proposals that could be implemented in construction and building materials industry, in compliance to environmental legislation demands and experience gained through reviewing negative aspects of practices used in the past and up till the present [9-11].

The majority of scientific papers dealt with studying composite materials manufacture using various other kinds of wastes as reinforcement in order to produce materials of low cost and respectively good mechanical and/ or thermal properties, such as agricultural waste [12, 13, 14], waste produced by industry applications or recycling facilities [15-19].

A representative number of articles focused on analyzing best practices of CDW recycling, in the context of sustainable development and circular economy [20-22]. Other researchers have carried out studies examining the requirements under which wastes deriving from various infrastructure projects, can be used in production of concrete or other building materials [23-25], or reused in new infrastructure applications [26,27-30].

Many research groups have been concentrated in studying potentials of developing new waste management models [31, 32, 33], and/ or describing existing implemented practices [33-35] of manufacturing cheap and competitive materials.

During the last decades, composite materials have been extensively used in many applications, such as aircraft industry, building and construction applications, medical and biomedical equipment, automotive and motorsports industry, electrical equipment manufacturing and many others, as a result of their excellent mechanical, thermal and other characteristic properties [36-39].

This study investigates and presents the potentials arising from CDW re-use in order to produce environmentally friendlier materials that also demonstrate respectively good mechanical properties. In addition to that, it introduces an alternative path which could boost up the CDW recycling performance levels worldwide.

## Materials and Methods

Raw materials – Process routine

Mixture of CDW containing bricks, gravel, tiles, soil, glass, concrete, wood, insulating materials and plastic has been processed and finally pulverized. The above waste was collected from a specialized CDW management facility based in the Menidi, Attica (Greece).

In order to investigate the possible changes in PMCs' mechanical properties once CDW micro-particles of different grain size are encapsulated within the polymer-matrix, two different sizes (300 μm and 500μm) of CDW micro-particles powder were (homemade) prepared. The complete preparation process path followed is presented in Figure 1.

Resin system used

The epoxy resin used as matrix for composites is Epoxol 2874 (Brand Name-Neotex) system, which is available in the market as a complete set (resin and curing agent).

Mechanical behavior investigation (polymer matri)

Prior to fabrication of composites containing CDW, an extended study on the mechanical behavior of resin system to be used as matrix for these materials was carried out. For the PMCs' fabrication, mixture of Epoxol 2874, by adding the selected curing agent was prepared by stirring the two ingredients for about 5 min, pouring it then into a specific mold for tensile stress and thermally curing it at 60 ºC. Pure epoxy composites with varying (w/w) quantities of curing agent and different thermal processing periods were prepared.

The impact of using different resin/ hardener mixture ratios in combination to gradual increase of thermal curing time on PMC's mechanical behavior has been studied.

Mechanical behavior investigation (composites with CDW)

To investigate how mechanical performance of composites is affected in case, a) CDW micro-particles powder of different sizes, b) different concentrations of powder are added in the composite, PMCs' containing CDW micro-particles powder with grain sizes of 300μm and 500 μm, and concentrations of 30%, 40% and 50% (w/w) were produced. Composite materials fabrication followed the same process as the one described above for pure epoxy composites.

Experimental tests were carried out and mechanical properties of the produced materials were monitored and analyzed.

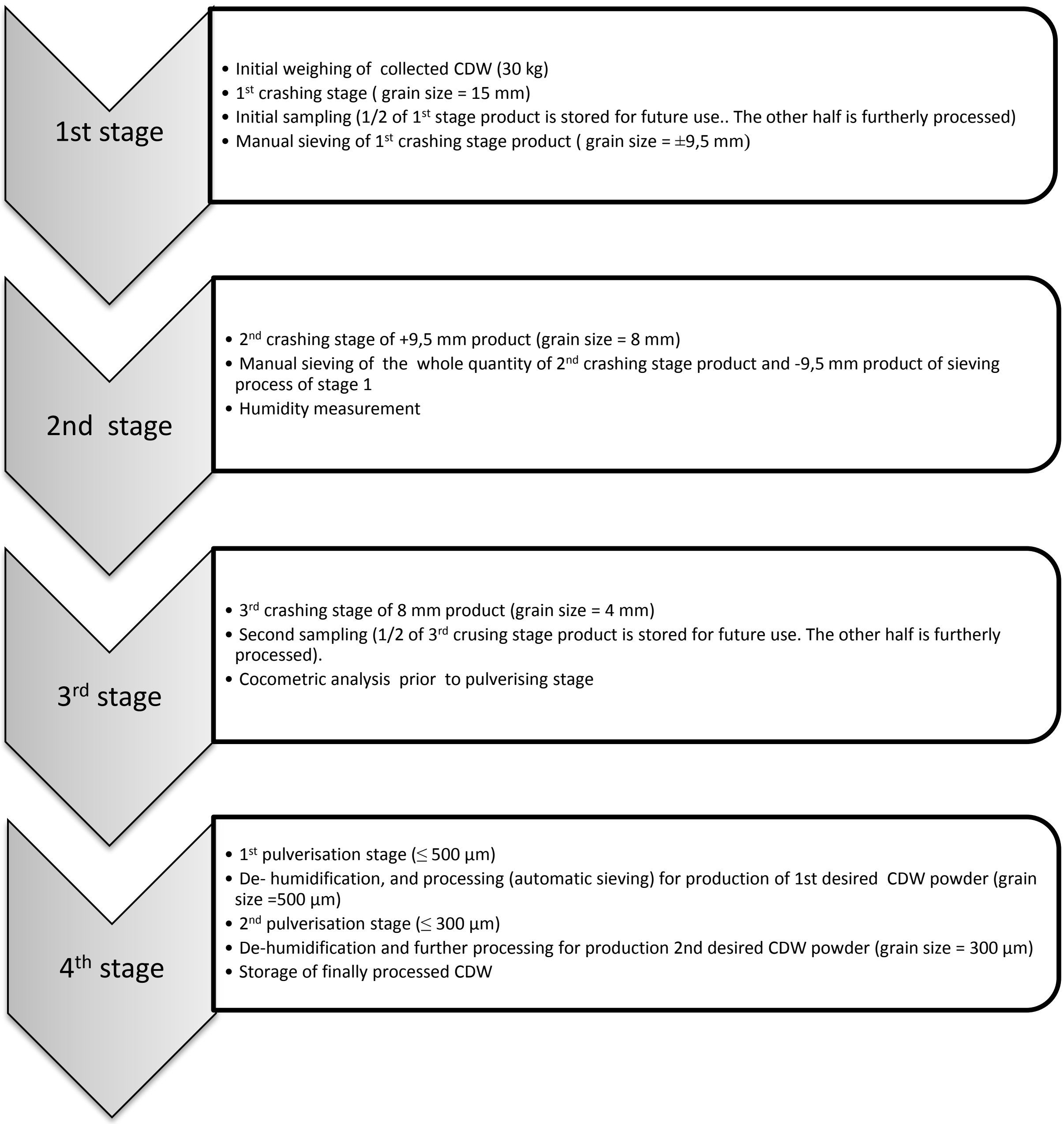


**Fig. 1** CDW process flow chart.

Experimental methods implemented

Experimental procedures used throughout this research, are in full compliance with ASTM D 2344/D 2344M (Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates) and ASTM D 790-71 (Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials), the officially established standards applied in experimental tests of shear and flexural strength respectively.

## Results and Discussion

Clear epoxy resin composites

*Flexural strength*

Test results on pure epoxy composites flexural strength are presented in Table 2 and Figure 2. It can be deduced that differing resin /curing agent ratio within the mixture, leads to modification of PMCs' mechanical behavior.

More specifically it was observed that for the majority of examined composites, the increase of curing agent's quantity within the mixture results to improvement of their flexural strength. PMC materials thermally cured for a time period of 4h form the only exception concerning this general remark.

Composites thermally processed for 2h presented improved flexural strength of 17.8 % once the polymer mixture analogy (epoxy/ curing agent) was changed from 98/60 to 88/70. In the case of composites cured for 4h, a decrease of 16% was observed. Finally for composites treated for a 6h time period, increase of hardener within the mixture, led to an increase of 53.6% in flexural strength.

Change of mechanical performance in this case, can be attributed to the elastomeric behavioral pattern of these particular materials. During the experimental procedure they demonstrated great flexibility and elasticity (i.e. no permanent deformation or break), fact which actually limited down their flexural strength in magnitude.

Thermal curing time is of equal importance as confirmed by the PMCs' response during the experimental tests. For composites with mixture proportion of 98/60, an increase of flexural strength of 27% and 9.6% is observed when curing period is increased from 2h to 4h and from 4h to 6h respectively. For 88/70 PMCs' a decrease of 6.3% in flexural strength comes as result of increasing thermal processing period from 2h to 4h. Further increase of curing time from 4h to 6h leads to increase about 65% in flexural strength. Mechanical performance inferiority of 88/70 composite thermally processed for 4h may be related-as mentioned above-to the elastomeric performance demonstrated by this specific composite.

On the other hand considering the fact that all other PMCs', exhibited improvement on their flexural strength for both investigated parameters (i.e. mixture ratio, curing time), the behavior pattern demonstrated, can be attributed to failure during the manufacturing process of the composite, such as air bubbles entrapment, bad quality stirring etc.

*Shear strength*

Experimental test results on pure epoxy resin PMCs' shear strength are presented in Table 2 and Figure 3. Differentiation of resin /curing agent proportion within the polymeric mixture, significantly affects composites' mechanical performance.

Increasing the hardening substance concentration (w/w) within the mixture leads to improved shear strength values, except for composites thermally cured for a time period of 2h. Change of mixture proportion in this case had as result the decrease of 38% in composites' shear strength. Performance inferiority may again be related to possible failure during the initial preparation stages of the composite material. Improvement of 8.71% in shear strength was demonstrated by 4h cured composites following the change of polymeric mixture from 98/60 to 88/70, percentage which climbs up to 57.5% when 6h is set as time period of thermal processing.

Curing time constitutes another key feature which has significant impact on the PMCs' mechanical behavior. For 98/60 ratio composites, an increase of 18% in shear strength is observed when thermal processing time is increased from 2h to 4h. For 88/70 ones this percentage rises up to 54%. Further increase of curing time, from 4h to 6h, results to a significant decrease of 36.3% and an increase about 11.1 %, for 98/60 and 88/70 composite materials respectively.

**Table 1.** Mechanical properties of pure epoxy resin composites.

| Resin/hardener mixture analogy (w/w %) | Curing time (h) | Fl. Strength ($N/mm^2$) * | Shear Strength (N/mm2) * |
|---|---|---|---|
| 98/60 | 2 | 70.21 | 9.22 |
| 88/70 | 2 | 85.47 | 5.71 |
| 98/60 | 4 | 95.65 | 11.2 |
| 88/70 | 4 | 80.38 | 12.27 |
| 98/60 | 6 | 105.82 | 5.86 |
| 88/70 | 6 | 227.92 | 13.8 |

* All Measurements include +/- 7% of error

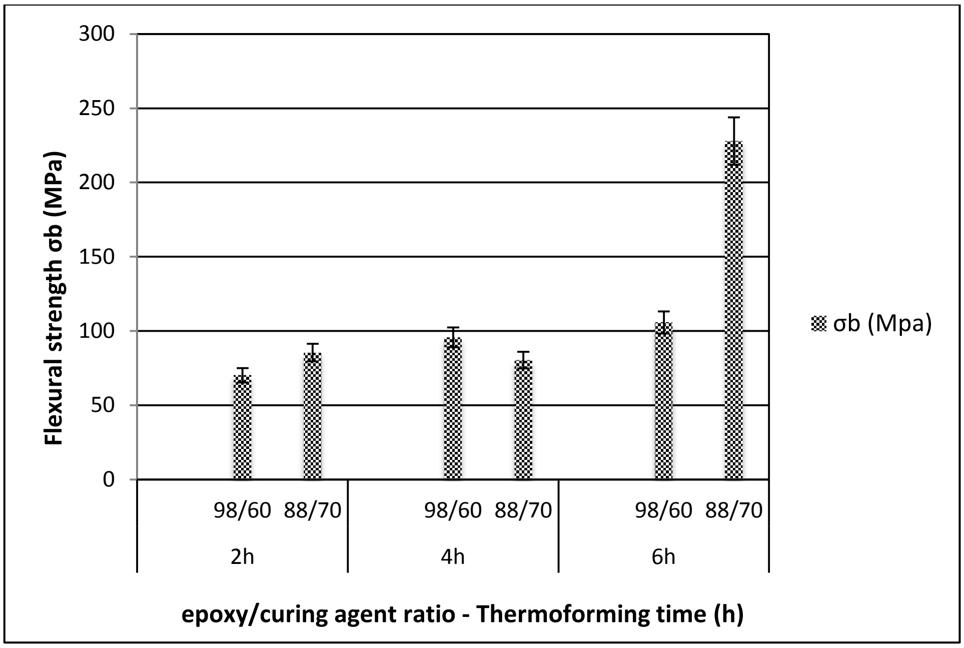


**Fig. 2** Graphical representation of flexural strength results (pure epoxy composites).

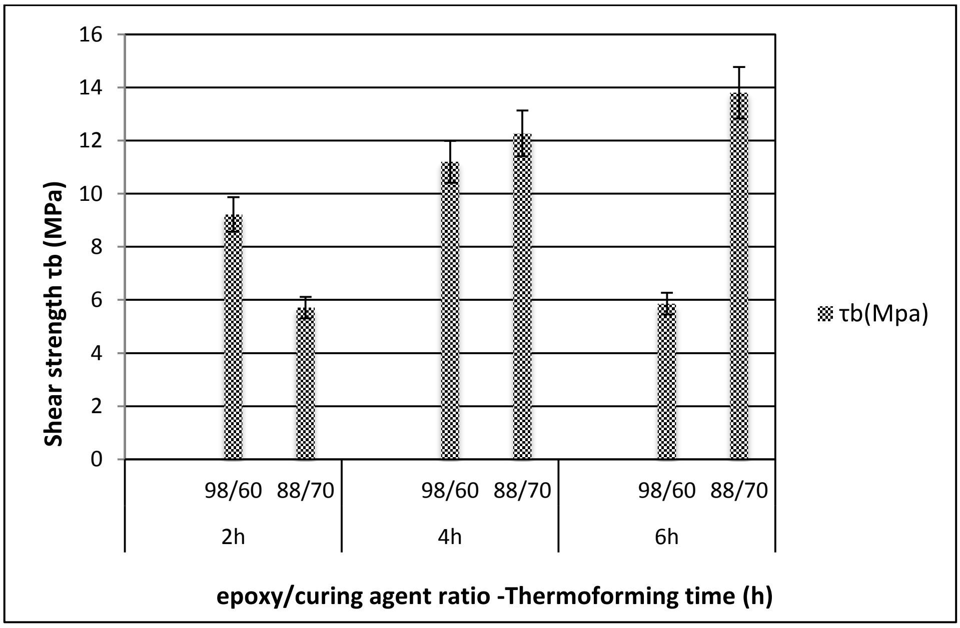


**Fig. 3** Graphical representation of shear strength results (pure epoxy composites).

CDW micro-particles filled composites

*Flexural strength*

Results of experiments carried out on composite materials loaded with CDW are presented in Table 3 and Figure 4. As it can be observed, the addition of micro-particles within the composite's body leads to downgrading of flexural strength.

Flexural strength is downsized by 73.7% (300 μm) and 84.8% (500 μm) once the w/w concentration of reinforcement content rises from 0% to 30%, i.e. once the initial addition of CDW powder takes place in the composites.

Increasing loading material's (w/w) percentage to 40%, leads to a decrease of flexural strength about 26.5% (500 μm) and 33.9% (300 μm). Further increase from 40% to 50%, results to even greater decrease of flexural strength values about 0.04% (for particles of 500 μm) and 33.4% (for particles of 300 μm).

Another parameter which strongly affects PMCs' mechanical behavior is the actual sizing of encapsulated CDW micro-particles. Using filling content of different grain size, leads to variation of the mechanical response of composite materials under study.

More specifically, composites incorporating 30% CDW (w/w %), exhibit a decrease of 42.3% in flexural strength once 500 μm CDW powder is used (as filler) instead of 300 μm one. Similarly composite materials containing 40% and 50% of CDW micro-particles, demonstrate a decrease in flexural strength about 35.9% and 7.7% respectively while grain magnitude of encapsulated particle- powder increases from 300 μm to 500 μm.

*Shear strength*

Composites mechanical response in terms of shear strength follows a similar behavioral pattern as it can be observed through examining the related experimental results, presented in Table 3 and Figure 4 below.

First addition (0% to 30%) of filling material within the composites has as outcome the decrease of shear strength by 45.3% for particles powder of 300 μm and 73% for 500 μm respectively.

Raising the percentage of micro-particles powder to 40% (w/w) leads to further decrease of PMCs' shear strength by 52.6% for composites incorporating particles of 500 μm and by 8% for composites incorporating 300 μm particles respectively. Further increase of contained CDW powder to 50% brings upon further reduction on composites' shear strength by 40.1% once 500 μm particles are used as additive substance. Respectively in the case of 300 μm particles, the reduction on shear strength is approximately 26%.

Granular sizing of filing substance's particles is again of significant importance. Once bigger size particles are enclosed in the composites, an inversely proportional decrease of shear strength is observed. In particular incorporating CDW particles 500 μm instead of 300 μm leads to reduction of shear strength by 50.6%, 4.2% and 22.9% for composites containing 30%, 40% and 50% (w/w) of CDW micro-powder as filler respectively.

**Table 2.** Mechanical properties of PMCs' (reinforced with CDW micro-powder).

| Particles magnitude (μm) | Matrix/ CDW (% w/w) | Fl. Strength ($N/mm^2$) * | Shear Strength (N/mm2) * |
|---|---|---|---|
| 500 | 70/30 | 34.59 | 3.72 |
| | 60/40 | 25.43 | 3.42 |
| | 50/50 | 24.42 | 2.05 |
| 300 | 70/30 | 60.03 | 7.54 |
| | 60/40 | 39.68 | 3.57 |
| | 50/50 | 26.45 | 2.66 |

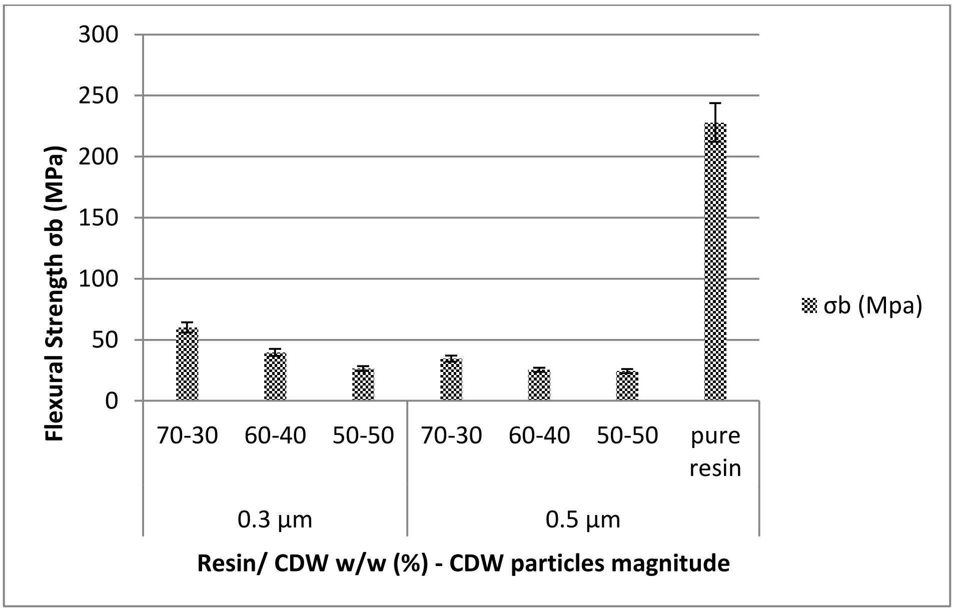


**Fig. 4** Graphical representation of flexural strength results (CDW micro-particles loaded composites).

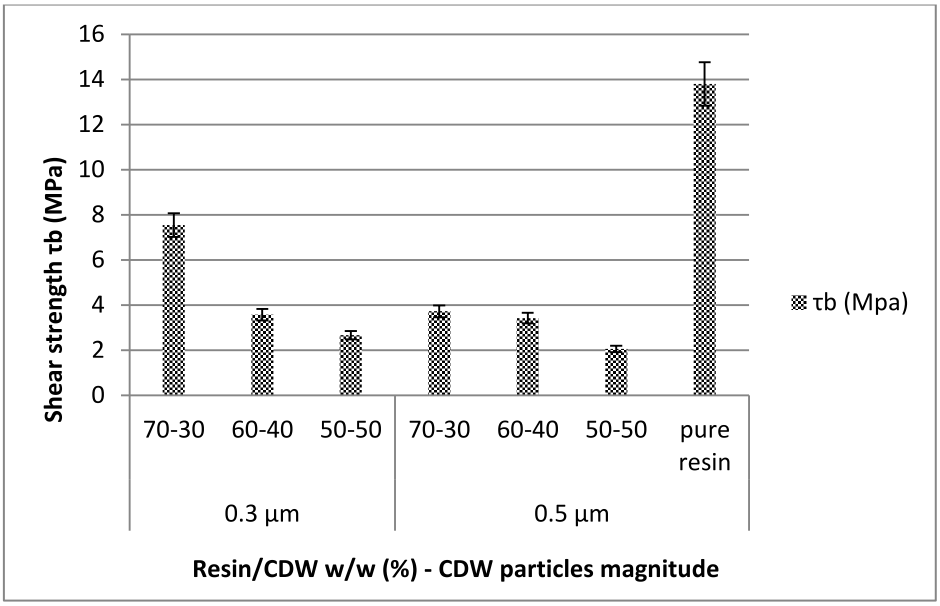


**Fig. 5** Graphical representation of shear strength results (CDW micro-particles loaded composites).

**Conclusions**

This study introduces an innovative method of CDW recycling, through their exploitation in composites as substitutes of primary resource materials.

Finally produced composites, exhibit respectively good mechanical properties, with magnitudes varying from i) 60.03 to 26.45 MPa for PMCs' encapsulating micro-particles of 300 μm and ii) 34.59 to 24.42 MPa for PMCs' encapsulating micro-particles powder of 500 μm as far as flexural strength is concerned and iii) from 3.72 to 2.05 MPa for PMCs' filled with CDW micro-particles of 500 μm and iv) 7.54 to 2.66 MPa for PMCs' filled with micro-particles powder of 300 μm for shear strength respectively.

Composites' mechanical behavior is strongly affected by changing specific parameters, such as curing time, resin/ curing agent analogy, concentration (w/w) and grain size of filling powder.

Optimum values of flexural and shear strength respectively were delivered for composite materials with curing time = 6 h, mixture ratio (w/w) = 88/70, micro-powder concentration (w/w) = 30 %, micro-particles grain size = 300 μm. The most important parameter as far as mechanical properties of the final composites are concerned, is thermal curing time followed by filling CDW micro-powder grain size and concentration (w/w).

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