Analysis of the Mechanical and Thermal Behaviour of Mortars Manufactured with Combined Use of Different Waste Products

P Badilla¹, V Letelier¹, P Aros¹, F Careau¹

¹Department of Civil Engineering. Universidad de La Frontera, Temuco, Chile

E-mail: pablo.badilla@ufrontera.cl, viviana.letelier@ufrontera.cl, patricia.aros@ufrontera.cl, f.careau02@ufromail.cl

Abstract. The present study analyses the incorporation of wastes into mortars, and the mechanical and physical response in mortars to the incorporation of these materials. Dosing must be such as to ensure that the test samples present a nominal degree of resistance of G-30. Recycled aggregates (RA) were obtained from the waste area of the prefabricated pieces production plant of Industrial y Comercial Burzio, Temuco, Chile, while biomass ash (BM) and crumb rubber (CR) were supplied by companies interested in the treatment and recycling of their waste. The matrix for the distribution of the replacement percentages was drafted using Taguchi statistical design, replacing natural aggregates with RA in proportions of 25% and 50%; CR was used to replace fine aggregates in proportions of 10% and 20%, and BM in proportions of 10%, 15% and 20%. Use of the study materials showed that with 10% of R, the mechanical properties were reduced; and that as the percentage of CR increased, the thermal conductivity diminished. The substitution of BM in a proportion of 10% increased the compression resistance and diminished conductivity by 20%. In the case of RA, the mechanical resistance was not diminished considerably compared to the control test samples, while the thermal conductivity diminished as the percentages of replacement material increased. The results showed that series S1 (0% RA, 0% R, 10% BM) and S2 (50% RA, 0% R, 15% BM) provided a compression resistance greater than 30 MPa, precisely the series which include no CR in the dosing. This result suggests that superficial pre-treatment of crumb rubber must be included in future experiments.

1. Introduction

One of the biggest environmental problems in the world today is the production of worn-out tyres. Their uncontrolled storage and slow degradation cause environmental pollution. According to Guillermo Castro [1], when this waste is burnt it produces gas emissions containing noxious particles. The Chilean Environment Ministry [2] indicates that “in Chile around 2.7 million worn-out tyres are generated each year, equivalent to approximately 46,000 tons of waste”. It is therefore very important to recycle this waste, reducing its serious impact on the environment.

The report on the treatment of solid wastes in Chile by Contreras M. [3] analyses different sectors of the cement industry. One of these is the building industry, which presented an increase in waste production of 72%, from 3.38 to 5.82 million tons, between 2000 and 2009. This report indicates that 78.7% of the total waste of the building industry is generated by aggregates. According to Pavón,
Etxeberria and Martínez [4], making concrete with RA is attractive as it provides greater durability than conventional concrete.

Traditional Portland cement is known to be one of the most widely used building materials. It has been estimated that replacing 18% of Portland cement would result in a 17% reduction in CO₂ emissions [5]. Demis et al. [5] indicate that there is an optimum replacement percentage for the development of compression resistance, above which resistance diminishes; this is attributed to the rapid initial rate of the pozzolanic reaction. This finding is supported by Barbosa et al. [6], who found that the highest compression resistance was obtained with 18% replacement, and that above 30% the mechanical resistance values were very inferior to those of the control mixture.

Cement mixtures prepared with the incorporation of waste CR as a replacement for fine aggregates present mechanical deficiencies which have been studied [7]. Some authors have evaluated different methods in order to improve their mechanical properties; however, the results have been variable [8, 9].

This article presents the experimental results obtained for the mechanical and physical properties of hybrid mortars. To determine the behaviour of mortar with the three wastes, RA, CR and BM, they were used to replace the traditional components of cement in different percentages, based on Taguchi design. The replacement fractions were selected based on data from previous studies, in order not to reduce the mechanical resistance to below 50% of that of traditional mortar.

2. Procedure
Four variables were chosen in preparing the mortar series: percentage of RA, percentage of R, percentage of BM and size of BM. The Taguchi design was used to obtain nine combinations, apart from the control series of traditional mortar (see Table 1).

The design of the L9 level orthogonal matrix assigned the 4 variables in 3 different quantities and sizes. Experimentation allowed the influence of the percentages of each material on the mechanical and physical magnitudes studied to be determined more accurately.

The replacement percentages were selected on the basis of previous case studies. According to Barbosa et al. [6], the highest mechanical resistance values obtained by replacing cement with BM were found when not more than 20% of cement was replaced.

In the case of RA, Leal et al. [12] indicate that the density values in a mixture prepared with RA were reduced by up to 2.0% when the replacement percentage does not exceed 50%.

The experimental work of Youssf et al. [7] shows that the replacement of fine aggregates by CR in a mixture must not exceed 20% to avoid loss of mechanical resistance higher than 40%. Unlike other materials studied, the replacement must be calculated by volume and not by mass, due to the considerable differences in density between aggregate and R.

| Series | Replacement percentage | Sieve size |
|--------|------------------------|------------|
|        | RA  | R  | BM |          |
| CONTROL| 0   | 0  | 0  | N/A       |
| S1     | 0   | 0  | 10 | 100       |
| S2     | 0   | 10 | 15 | 200       |
| S3     | 0   | 20 | 20 | 325       |
| S4     | 25  | 10 | 10 | 325       |
| S5     | 25  | 20 | 15 | 100       |
| S6     | 25  | 0  | 20 | 200       |
| S7     | 50  | 20 | 10 | 200       |
| S8     | 50  | 0  | 15 | 325       |
| S9     | 50  | 10 | 20 | 100       |

Table 1. Study series in mortars
2.1. Materials

2.1.1. Recycled aggregates
RA was used to replace both the fine and coarse fractions of natural aggregates. The material was obtained from elements rejected from the production line of Industrial y Comercial Burzio, Temuco, Chile. The process included crushing and washing in a rotating cylinder to remove remains of cement from the surface of the aggregates, which reduces the adherence of RA in the new concrete. The granulometric range of the material was between 6.3 mm and 0.075 mm mesh aperture.

2.1.2. Crumb rubber
Experimental studies on materials made with Crumb Rubber Concrete (CRC) have shown that the use of CR in mortars and concrete mixtures improved parameters such as ductility, tenacity, resistance to impact, energy dissipation and shock absorbance factor; however, it reduced the resistance to compression and traction and the elasticity module as compared to a conventional concrete. The reasons for this reduction are the low hydraulic conductivity and smooth surface of the CR particles, resulting in poor adherence between CR and the cement. The CR used was obtained from worn-out tyres; it was produced by an automobile services company which shreds and granulates the CR and separates it from the steel or textile fibres which form part of the tyres.

2.1.3. Biomass ash
The quality of the ash produced in a biomass plant is strongly influenced by the origin of the biomass: agricultural waste, grasses and wood or bark are among the possible elements used as the base material. The BM used in this study was forest biomass, a by-product of the energy cogeneration processes related with the forest products industry.

![Image](a) fine fraction recycled aggregates, (b) rubber after sieving through a #30 mesh, (c) biomass after drying in an oven

2.2. Assays

2.2.1. Normal Consistency Assay (Fluidity)
This assay shows the degree of fluidity of the mixture, which improves its workability; the quantity of water needed for dosing was calculated. The method was applied according to NCh 2257/1 Of. 1996 by extension on a shaking table; this produced a diameter in the range of 210 ± 5mm, which allowed the water/cement (W/C) ratio to be calculated.

2.2.2. Flexion and compression assays
Assay standardized by NCh 158 Of. 1967, which determined the mechanical resistance to compression and flexion forces of the mortar series at 7, 14 and 28 days, in “Rilem” prismatic test samples of normalised dimensions.
2.2.3. Density and absorption coefficient assay
This assay was used to obtain the absorption percentage, density and open porosity in hardened mortars. The assay is based on UNE-EN norms 1015-18:2003 and 1015-10:2003. Cylindrical test samples 50 mm high and 100 mm in diameter were tested; they were dried at 105°C to constant mass and then submerged in water to obtain the saturated mass.

2.2.4. Ultrasound velocity test
This test was used to determine the presence of cracks and bubbles and the homogeneity of the test samples. The assay was carried out in cylindrical test samples 50 mm high and 100 mm in diameter, cured for 28 days. The test equipment used was the “Ultrasonic Pulse Analyzer”; the methodology followed BS 1881: Part 203: 1986.

2.2.5. Thermal conductivity assay
Assay based on norm ASTM D5334-08. The thermal conductivity of the mortars was obtained by thermal needle probe, using cylindrical test samples 50 mm in diameter and 150 mm high.
Before the assay the test samples were heated at 70°C for 24 hours and then conditioned at 20°C for a further 24 hours.

3. Results and discussion

3.1. Mechanical resistance

3.1.1. Flexion
The results obtained show that with the incorporation of 10% of BM (S1), the flexion resistance increases by 5.85% over the control mortar. When series S6 was compared with S8, its mechanical resistance was found to be reduced; it is therefore assumed that 20% of BM is not a good value for improving the mechanical resistance. It is inferred that the loss in resistance is due to the excessive percentage of BM. It would therefore be feasible to use between 10% and 15% of BM to increase or maintain the flexion resistance of the mortar.

With the replacement of coarse aggregates by RA, a trend is observed for the flexion resistance to diminish. The lowest value was obtained with a replacement percentage of 50%, plus replacement of 20% fine aggregates by R. In series S8, it was observed when the RA replacement is kept at 50% and no CR is incorporated in the mixture, the results are not very different to those of a control mixture at 7, 14 and 28 days.

![Graph 1. Flexion resistance in mortars](image-url)
As Graph 1 shows, all the series with 20% replacement by crumb rubber present resistances less than or equal to 5.04 MPa. The incorporation of wastes tends to diminish resistance to flexion forces; these effects are strong when the waste incorporated is R, and the replacement percentage must be restricted for this reason.

3.2. Compression

Graph 2 shows that a BM replacement percentage of 10% in series S1 produces an increase in the resistance to compression forces of 4.83% over the control series after 28 days. Series S8 presents a diminution of 7.2% in its compression resistance; it is known that using a replacement percentage of up to 50% RA produces minimal reductions in the mechanical properties.

According to Vegas and Juarrero [10] up to a maximum of 25% RA can be incorporated without showing loss of mechanical properties.

![Graph 2. Compression resistance in mortars](image)

When crumb rubber is used in a replacement percentage of 20% (series S5 and S7), the resistance falls to 62.33% and 61.33% respectively compared to the control series for test samples assayed after 28 days; these series, together with S3, had the highest replacement percentage of crumb rubber in their dosing and show the influence of this waste material on compression resistance.

3.3. Density and absorption coefficient of mortars

Graph 3 shows that the series with the highest quantity of CR present the lowest densities, due to the physical properties of crumb rubber.

According to the results of Rivas [11], with 30% replacement of RA, the density diminishes by 1.86% from that of traditional mortar. This author also reports the use of CR as a partial replacement at 10%, which caused a reduction of 7.76% in the apparent density.

RA has a lower density than natural aggregates, so the density of a mixture with this waste will be lower than that of a conventional mixture, by up to 2.0% with 50% replacement [12].
The absorption percentage increases, independent of the type of waste incorporated into the mortar; therefore, the higher the replacement percentage with the wastes studied here, the higher will be the absorption coefficient. When the control series is compared with S1, a minimal tendency is found for the percentage of this parameter to increase, thus with 10% replacement by BM the absorption increases by only 0.73%. When series S5 and S7, with 20% R, are compared, it can be inferred that the cause of the increase in the absorption percentage is the partial replacement with RA. Therefore, the greater the replacement percentage of RA, the greater will be the absorption percentage of the mortar [11].

3.4. Ultrasound velocity
The ultrasound pulse velocity diminishes (by 1.83%) with the use of 10% BM only (series S1). In Graph 4, if series S6, containing 25% RA and 20% BM, is compared with series S8, containing 50% RA and 15% BM, a lower velocity is observed in S6 than in S8, from which we may conclude that the extra 5% of BM in S6 is more significant than the 25% of superior RA in S8. We conclude that BM has a greater impact on ultrasound velocity in the mortar than RA.
From the assay it may be inferred that the incorporation of waste products is directly proportional to the elastic parameters of the mortar. We conclude that neither BM nor RA as partial replacements cause very great variations in the resistance properties of concrete.

3.5. Thermal conductivity
Graph 5 shows a clear tendency for the thermal conductivity to diminish in inverse proportion to the increase of BM. In series S6 and S8, in which replacement percentages of CR were not included in the mixture, the thermal conductivity was higher than in the other series where CR was included. This supports the theory that CR has excellent thermal properties as a material resistant to heat transmission.

RA makes an important contribution to thermal conductivity; in the first two series – including the control mixtures – where the content is zero, the thermal conductivity values are higher than 0.75 W/mK. As RA is incorporated, along with BM and R, the thermal conductivity values tend to diminish more or less in line with the replacement of R. According to Tam et al. [13], the effect can be attributable to the porous nature of the recycled aggregate, and hence, the premix process can fill up some pores and cracks, resulting in a denser concrete, an improved interfacial zone.

As Graph 5 shows, the series with the lowest thermal conductivity are those with the highest percentage of CR as partial replacement, diminishing the thermal conductivity by 33.67% in S7 compared to the control mixture.

3.6. Comparative analysis of mortars
From Graph 6, the correlation existing between the density and the compression resistance may be inferred.
As there is little cohesion between the particles of CR and the rest of the components of the mortar, internal cracks occur which are directly related with the quality of the mortar; this explains the directly proportional relation between the compression resistance and the quality of the mortar (see Graph 7).

As Graph 8 shows, the density is directly proportional to the ultrasound velocity, i.e. the series with lower densities contain a larger number of air bubbles and therefore the velocity of wave propagation will be lower.
This tendency is even more marked in the relation between the density and the thermal conductivity; as Graph 9 shows, the lower the density, the lower the thermal conductivity, since the pores and their air content increase.

Graph 9. Thermal conductivity v/s density

4. Conclusions
The use of RA and CR diminish the mechanical resistance of mortars due to the lower density of these materials. The use of BM increases the mechanical resistance by 4.83% compared to traditional mortar, so long as the replacement percentage does not exceed 10%.

The incorporation of RA in proportions of 25% and 50% to replace natural aggregates diminishes the mechanical resistance to flexion and compression forces. From the results obtained it can be inferred that RA can be replaced without reducing the mechanical properties of the mortar if the replacement is restricted.

Replacement with CR diminishes the mechanical resistance of mortars considerably, and it should not be used to replace fine aggregates in a proportion greater than 15%. The diminution in the resistance to mechanical forces is due to the low surface rugosity of CR and therefore to lower cohesion between the CR and the cement. The maximum recommended replacement percentage is 10%.

R has a great capacity to reduce the thermal conductivity and density of mortars. The series which incorporate 20% of CR presented thermal conductivity values below 0.6 W/mK; a similar trend is found in the density of the samples, which diminishes when the replacement percentages of CR are higher. This is due to the structure of crumb rubber, which contains a large number of air bubbles.

Acknowledgements
This analysis is part of the Project DIUFRO DI19-0019 (‘‘Desarrollo de una dosificación de morteros con baja conductividad térmica para utilizar en prefabricados’’), funded by the Universidad de La Frontera.

References
[1] Castro G. 2007. Reutilización, reciclado y disposición final de neumáticos. Presentación de cátedra. Departamento de Ingeniería Mecánica, Universidad de Buenos Aires.
[2] Ministerio del medio ambiente 2008. Diagnóstico fabricación, importación y distribución de...
neumáticos y manejo de neumáticos fuera de uso. Diagnostico-neumáticos 2008. Santiago.

[3] Contreras M. 2009. Planta de tratamiento integral de residuos de la construcción y demolición. Tesis de pregrado. Facultad de Arquitectura y Urbanismo, Universidad de Chile.

[4] Pavón. E, Etxeberria. M y Martínez I. 2011. Propiedades del hormigón de árido reciclado fabricado con adeciones, activa e inerte. Revista de la construcción, vol. 10 (3), pp. 4-15.

[5] Demis, S., Tapali, J G., Papadakis, V. G. 2014. An investigation of the effectiveness of the utilization of biomass ashes as pozzolanic materials. Construction and Building Materials, vol. 68, pp 291-300.

[6] Barbosa, R., Lapa, N., Dias, D., Mendes B. 2013. Concretes containing biomass ashes: Mechanical, chemical, and ecotoxic performances. Construcccion and Building Materials, vol. 48, pp 457 – 463.

[7] Youssf, Mills, Hassanli 2016. Assessment of the mechanical performance of crumb rubber concrete. Construction and Building Materials. Vol 125 (295), pp 175-183.

[8] Letelier, V., Ortega, J.M., Muñoz, P., Tarela, E., Moriconi, G. (2018). Influence of Waste brick powder in the mechanical properties of recycled aggregate concrete. Sustainability 10(4),103. doi: 10.3390/su10041037.

[9] Letelier, V., Tarela, E., Muñoz, P., Moriconi, G. Assessment of the mechanical properties of a concrete made by reusing both: Brewery spent diatomite and recycled aggregates. Construction and Building Materials 114, pp. 492-498. doi: 10.1016/j.conbuildmat.2016.03.177

[10] Vegas, Azkarate, Juarrero, Frías 2009. Diseño prestaciones de morteros de albañilería elaborados con áridos reciclados procedentes de escombros de hormigón. Revista Materiales de construcción. Vol 59 (295), pp 5-18.

[11] Rivas Sebastian 2018. Estudio y análisis de la incorporación de materiales reciclados como componentes de mortero. Tesis de pregrado. Departamento de Ingeniería en Obras Civiles, Universidad de la Frontera.

[12] Leal, Osses, Valdés, Letelier, 2012. Utilización de áridos reciclados para la evaluación de las propiedades de Resistencia mecánicas, permeabilidad y contenido de aire en hormigones de grado estructural H-30. Revista Científico Tecnológica Departamento Ingeniera de Obras Civiles RIOC. Vol 1. Pág. 99-112.

[13] V.W.Y.Tam, X. F. Gao, C.M.Tam 2005, Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach, Cem. Concr. Res 35 (6) (2005), pp 1195-1203.