



A water-soluble core material for manufacturing hollow composite sections



Z. Xiao, L.T. Harper*, A.R. Kennedy, N.A. Warrior

Composites Research Group, Faculty of Engineering, University of Nottingham, NG7 2RD, UK

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ABSTRACT

This paper presents the development of a low-cost water-soluble core material, which is suitable for producing hollow composite structures via high pressure moulding processes, such as compression moulding and resin transfer moulding. The bulk material of the core is sodium chloride (NaCl), which is held together by a water-soluble trehalose binder. The composition of the core has been optimised to provide acceptable dissolution rates and mechanical properties for high volume structural composite applications.

The compressive strength of the NaCl core was 57 MPa at ambient temperature, which reduced to 20 MPa when tested at 120 °C. The compressive strength at elevated temperature was approximately 4 times higher than for a water-soluble commercial benchmark and 33 times higher than a conventional structural closed-cell foam. The specific dissolution rate of the NaCl core was between 0.14 and 1.23 kg/(min·m²), depending on processing parameters and the coefficient of thermal expansion was approximately $43 \times 10^{-6}/K$. A practical example has been presented to demonstrate how the removable core can be used to produce a representative hollow section of an integrally stiffened panel.

1. Introduction

Core materials are used to separate structural composite skins in order to increase the second moment of area and greatly improve the bending stiffness. Foam materials are commonly used to form sandwich panels, but current high volume composite manufacturing processes, such as compression moulding or high pressure resin transfer moulding (HP-RTM), can generate pressures of 30–150 bar inside the mould tool [1,2]. Closed-cell structural foams therefore typically require very high densities (for example 200 kg/m³ for a compressive strength of 6 MPa [3]) to prevent crushing in many applications. These materials tend to stay in the final moulding and therefore add parasitic mass.

Removable core materials are available and are commonly used for manufacturing hollow metallic structures, for example sand cores for casting automotive cylinder blocks [4,5]. Sand cores are held together by a binder material such as sodium silicate, which hardens when exposed to carbon dioxide [6]. Mechanical removal methods, such as shaking and knocking, are required to extract the sand, which can be difficult if access is limited or the component is fragile, as the bonded sand particles do not readily flow [6]. Plastics such as polyoxymethylene (POM) and low melting temperature metals such as zinc based alloys (ZnAl₄Cu₁) are also used to make cores, and can be burnt off or melted out at elevated temperatures [4]. The removal temperatures for extractable polymers (~180 °C) and metals (380 °C) are typically incompatible with the polymer matrix, or they are insufficiently

stiff and can crush under the moulding pressure. Caustic solutions containing sodium hydroxide may be used for removing ceramic-based cores [7,8], but this is harmful to the environment and can affect the mechanical performance of the finished product [9]. Current removable cores tend to be incompatible with high pressure moulding processes, as the resin can infiltrate into the core during the infusion process, impeding the core removal. Clearly there are opportunities for reducing the mass of structural composite components, but the challenge is finding a removable core material that can withstand high pressures during the moulding process, is impermeable to the low-viscosity resin, can be quickly and easily removed and can be manufactured at low cost.

This paper investigates the potential for using water soluble sodium chloride (NaCl) cores for producing hollow carbon fibre composites, similar to the ones that are used to produce high pressure die castings [10]. The cores consist of NaCl and a water-soluble and environmentally friendly binder, trehalose sugar, which can be hot pressed into shape. They can be simply washed out after the composite moulding cycle using water and can potentially be recovered. A study is presented to define a processing window for the NaCl core to achieve suitable mechanical properties for use in high pressure moulding processes (100–150 bar), whilst ensuring the core can still be removed from the composite, post moulding. The influences of binder content, processing pressure, temperature and time are all investigated.

* Corresponding author.

E-mail address: lee.harper@nottingham.ac.uk (L.T. Harper).

2. Background

The following criteria has been identified to ensure the core material is suitable for high pressure composite moulding processes:

- Sufficient compressive strength (typically 15 MPa) at elevated mould temperatures (typically 120 °C).
- Impermeable to low viscosity resins.
- Fully removable and within the Takt time of the moulding process (typically 5–30 min).
- Easily removable without inducing damage to the composite structure.
- Machineable or castable to produce complex geometries.
- Low cost.
- Recyclable and environmentally friendly.

Inorganic salts are an appropriate material choice, as commercial salt cores are reported to have flexural strengths of over 18 MPa [10] and have been used for high pressure die casting (HPDC) at temperatures and pressures exceeding 690 °C [4] and 60 MPa [11] respectively. Different compositions have been investigated in the literature, including KCl based cores for high bending strength at elevated temperatures [4,12], NaCl cores containing mica powder for cost reduction [7], NaHCO₃ based cores for accelerating core removal [13], and four binary systems (NaCl-Na₂CO₃, KCl-K₂CO₃, KCl-NaCl and K₂CO₃-Na₂CO₃) for increasing mechanical properties compared with NaCl cores [11]. The material is readily available and inexpensive and can be dissolved in water to enable the core to be washed out from the composite structure. There is also the potential to recover some salt from the waste solution.

There are typically three binding mechanisms for salt cores. These include 1) mechanical pressing of salt grains followed by sintering, 2) melting followed by consolidation and 3) adhesives (see Table 1). For sintering, salt particles are typically pressed at over 100 MPa and then thermally treated at 650 °C to increase the bending strength from 5 MPa to 9 MPa [4]. Whilst sintered cores have good mechanical properties and low porosity (reported as 2%–6% [4]), they are limited to producing simple geometries because a non-hydrostatic pressure is generated in the tool. The magnitude of the processing pressure is also an issue for larger scale components, due to the high capital costs for tooling and a hydraulic press. For the same reasons, casting liquid salt cores is not appropriate for large composite components. In addition, the energy consumption for producing cast liquid salt cores is high due to the high heat capacity and melting point of salt (800 °C) and the shrinkage of the core can be significant (> 15 vol%) following solidification [4,11]. The dissolution rate for dense salt cores is also very slow, requiring high pressure water jets (600 bar) to remove the core [14].

Using a binder to stabilise the salt core can effectively reduce the required consolidation pressure to less than 1 MPa [7], as a high level of mechanical interlocking of the salt grains is not required to achieve acceptable properties. The mixture can also be pressed warm or cold, depending on the binder used [4,7,12,13]. Binders used for salt cores are often sodium silicate (water glass), synthetic resins, and polyethylene glycol [4,7,12,13]. Compared to sintered cores, more complex shapes can be produced but the porosity level is much higher (up to

30% [4]), and therefore mechanical properties are lower. Depending on the binder type, the addition of such a parasitic material can have a negative effect on the dissolution rate [4].

3. Salt core development

For the current work, extra fine NaCl powder with an average particle size of 0.59 mm was used to manufacture the cores, referred to here as NT Cores. Trehalose sugar was used as the binder material, which had a powder particle size of < 0.30 mm. Trehalose is a non-reducing sugar formed from two glucose units joined by a 1-1 alpha bond. It is therefore water-soluble, compatible with NaCl and does not appear to affect the fibre reinforced composite. The powders were mechanically mixed to the required ratio and then poured into a pre-heated cylindrical mould with an inner diameter of 150 mm. The mould surface was coated with Frekote 700-NC mould release to aid removal of the core. The salt/sugar mixture was hot compacted and held at temperature, before the tool was cooled in the press at a rate of 5 °C/min. The core was demoulded when the tool temperature had reduced to 30 °C. Test coupons were machined from the round disc, typically 13 mm thick, using a 3 mm wide diamond tipped circular saw (see cutting plan in Fig. 1). Before machining, the dimensions and mass of each core were recorded to calculate the density.

3.1. Design of experiment

A Taguchi study was conducted to establish the relative significance of a range of processing variables on the strength of the NT Core at ambient temperature, and the dissolution behaviour in water. The independent variables and their associated levels are summarised in Table 2. Processing pressure directly influences the cost of the tooling and capital expenditure and therefore should be minimised to produce cost effective cores for high volume applications. The effect of binder content, processing temperature and processing time were all investigated as possible ways to compensate for lower processing pressures.

With a broad “processing window” defined, a more detailed second study was conducted to determine the effect of elevated in-service mould temperatures, with tests conducted at 80 °C and 120 °C. Two widely-used core materials were also tested as benchmarks: a structural closed cell foam (A Core) and a water-soluble material containing ceramic microspheres (B Core). The B Core material was moulded in the same circular tool as the NT Cores at a pressure of 17 bar at room temperature. The demoulded cores were subsequently dried in an oven at 125 °C for 1.5 h.

3.2. Experimental methods

3.2.1. Mechanical testing

Both 3-point bend and compression tests were conducted on an INSTRON 5985 universal testing machine. For 3-point bending tests, five 13 × 13 × 100 mm specimens were prepared for each material and a constant span of 60 mm was used between Ø10 mm support rollers for all specimens. Tests were performed at a speed of 1 mm/min. The applied force was recorded by a 25 kN load cell and the central

Table 1
Salt cores made by different processes and their mechanical property.

Manufacturing process	Core material	Flexural strength (MPa)	Comments
Sintering	KCl	> 9.0	Pressed at 104 MPa; Additives: ZrSiO ₄ , Al ₂ O ₃ , SiO ₂ , Fe ₂ O ₃ ; Heat treatment at 650 °C [4]
Binder	NaCl	2.1	Binder: water glass; Pressure: 7.5–8 bar [4]
	NaCl	6.6	Binder: polyethylene glycol and 10 wt% plasticizer; Pressure: 4–5 bar [7]
Liquid casting	NaCl	> 18.0	[14]
	NaCl Na ₂ CO ₃	> 30.0	NaCl-70 mol% Na ₂ CO ₃ [11]

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