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Load Carrying Elements and Structural Modular Systems Made of Synthetic Fibres Reinforced Mineral Matrix Composite

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Abstract. The use of recyclable materials is a priority for the construction industry aiming to a sustainable development. Recent works have shown that calcium sulphate in the β anhydride III' form which is a hydraulic binder manufactured from industrial wastes can partially replace ordinary Portland cement in construction elements. Alkali resistant glass fibres can be used as reinforcement for ecological mineral matrix in order to obtain a mineral composite material. In the framework of an extensive research program, load carrying elements and structural modular system entirely made of mineral composite material were designed, developed, tested, analyzed and implemented. The paper presents the selection of efficient mixes for a mineral matrix with convenient mechanical properties, good workability and encouraging prospects to be implemented in construction elements and full structural systems. The experimental work carried out confirms the suitability of this material for load bearing elements and modular building systems.

Introduction

From ancient times people have built shelters with accessible materials in areas where they lived. Most of the building structures used a combination between clay and twigs, branches, trunks of trees, chopped straw or animal hair. Technology have evolved and others materials have appeared. The new materials were designed to be stiffer and stronger, more adequate for complex types of building systems. Concrete, as the Romans knew it, was a new and revolutionary material. Laid in the shape of arches, vaults and domes, it quickly hardened into a rigid mass, free from stresses and strains that troubled the builders of similar structures made of stone or brick [1].

Modern concrete differs from Roman concrete in two important aspects: the mix consistency nowadays is fluid and homogeneous, allowing concrete to be poured into forms, and the use of reinforcing steel which gives modern concrete assemblies high strength in tension [2].

Joseph Aspdin, the British stone mason, credited with the invention of Portland cement in 1824, literally prepared the first batch in his kitchen. But Aspdin took this simple process one step further. On the stove he heated finely ground limestone and clay. The resulting substance, known as clinker, was cooled and ground into a fine powder. The beauty of Aspdin's cement and its modern descendants is that it can be stored dry in a bag, yet activated merely by the addition of water on the jobsite [3].

Portland cement (often referred to as Ordinary Portland Cement - OPC) is the most common type of cement around the world and it is a fine powder called clinker, made by heating, in a kiln, a homogeneous mixture of raw materials to a calcining temperature, of about 1450 °C. The manufacturing process is not ecological friendly and meeting the environment protection standards becomes an important objective in the context of sustainable development.

Materials

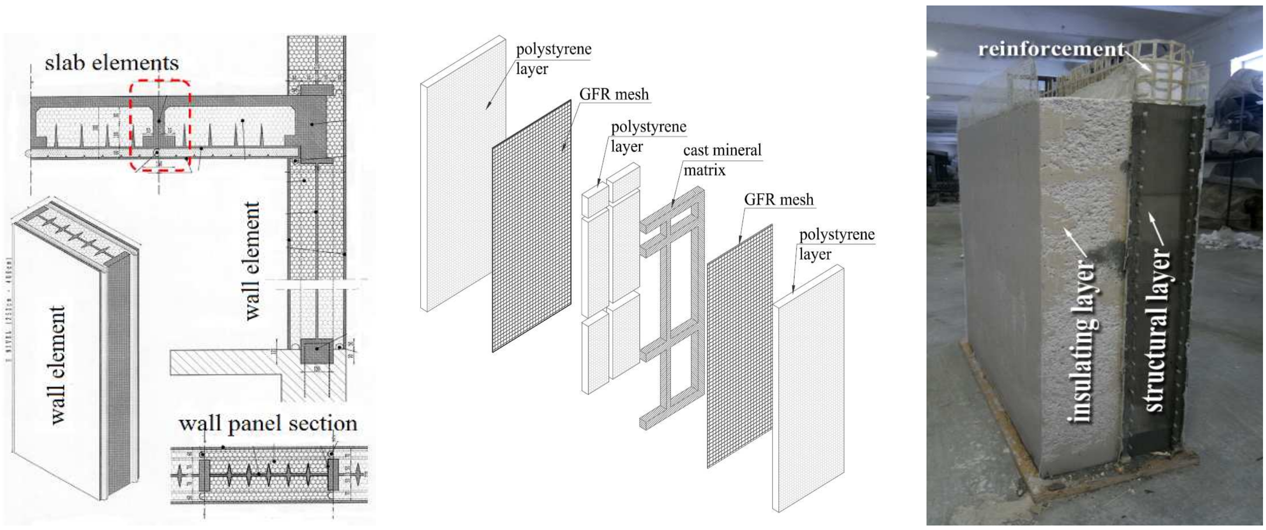
The use of recyclable materials is a priority for the building industry as well. Partial replacement of OPC with specific strong binders may be one step for using these materials. According to recent studies in France [4] it was observed that calcium sulphate in β anhydride III' form manufactured from industrial wastes can reduce the use of OPC in composition of some building materials and provide suitable mechanical characteristics as well. Thus, the new technology once expended on a large usage scale will reduce massively the emission of CO_2 and provide commanding contribution to environmental preservation and societal developments.

Since many industrial wastes are currently lying unused on the ground surface worldwide. This "green cement" technology becomes an ecological and economical alternative to the highly polluting OPC.

The new binder is entirely recyclable and can be used alone or as substitution of the OPC to produce various construction materials such as: mortars and concrete, insulating panels using polystyrene or polyurethane as aggregates and self-levelling floor screeds.

Research works on a mineral matrix capable of forming a composite material reinforced with glass fibres begun in the 1960s with the utilization of gypsum; later on the OPC has also been introduced as another solution for cementitious mineral matrices reinforced with glass fibres. [5, 6]. Composite solutions based on glass fibre reinforced mineral matrices have been conceived so that they become viable alternatives to traditional building materials such as wood, masonry or concrete [7, 8]. These new alternative solutions have led to more cost-effective construction elements with improved stiffness/weight and strength/weight ratios and enhanced thermal characteristics [9].

In the framework of a comprehensive research program, the main objective was developing of a new load carrying elements and structural modular systems using recyclable materials. In the first stage of the program, the materials were chosen by their accessibility on the market and their characteristics. The proposed building structure is a modular system made of panel units for walls and floor elements. In Fig. 1 the composition of the best three solutions for the wall elements as they evolved is presented.



a b c

Fig. 1. The composition of the wall panels units: a- first solution with 1 middle layer of composite material; b- second solution with 2 centred composite material layers; c- third solution with 2 composite material layers on interior side

In the first solution Fig. 1a, the wall element is composed by 1 middle layer of about 2 cm, of glass fibre reinforced mineral matrix composite (GFRMMC) and 2 insulating layer on each side of the panel. The second solution Fig. 1b, consist in 2 structural layers of about 1 cm of GFRMMC disposed on each side of a central insulating layer and 2 other insulating layer of about 10 cm on the exterior sides. The last solution Fig. 1c, the wall element is continuously cast in a vertical direction. The structural material is also GFRMMC and is mounted on the interior side. The length of the element is equal with the wall length. The insulating layer is cast on the exterior side and is composed by a mixture of polystyrene balls and calcium sulphate binder.

The research program started with the selection of the material components for the mineral matrix. These were combined in different proportion and tested to identify an optimum mix based on their mechanical properties and the workability criteria. Different proportion of sand and OPC were combined with anhydrous calcium sulphate in the β-anhydrite III' form as an ecological binder. This mixture (OPC and eco-cement) acts as a stable binder [10] that can form a mineral matrix capable of being reinforced with alkali resistant glass fibres for composite construction elements. To achieve the mineral matrix, the quartz sand washed and free of impurities with a grain size up to 1 mm, Portland cement type CEM II / BV 32.5 R and the eco-cement have been utilized. The basic characteristics of the Portland cement are shown in Table 1.

Table 1. Characteristics of CEM II/B-V 32.5 R Portland cement [11]

Cement type	Constituents	Chemical compounds	Setting time	Material properties	
				Density	Compressive strength
CEM II/B-V 32.5 R	Clincher Portland 65÷79%	Sulphate content max. 3.5 %	min. 75 min	3.2 g/cm^3	min. 32.5 N/mm^2
	Fly ash 21 ÷ 35%	Chloride content, max. 0.1 %			max. 52.5 N/mm^2

The reinforcement used for load carrying elements and laboratory samples tested is made of alkali resistant E glass fibre mesh 3.5 x 3.8 mm orthogonally arranged. The glass fibre mesh characteristics are presented in Table 2.

Table 2. E fibre glass mesh characteristics [12]

Characteristics	Units	Fibre glass mesh
Slot mesh	[mm]	3.5 x 3.8
Slot thickness	[mm]	0.52
Mesh density	[g/m^2]	160
Tensile strength	[N/mm^2]	2000
Tensile modulus	[N/mm^2]	72413
Fibre chemical treatment		alkali resistant without emollient obstructing yarn drifting

For the composition of the structural elements, expanded polystyrene (EPS) sheets have been used as formwork in case of modular panels and thermal insulation layer. The thermal conductivity of EPS is 0.038 W/(m·K) with the density of 15 kg/m^3.

Testing methodology

Structural building model made of mineral composite material. An important part of the research program consists in designing and building a modular structural system subjected later on dynamic and static tests. One storey structural model has been made of hybrid panels and tested using the shaking table at the Faculty of Civil Engineering and Building Services of Iasi. The perspective and corresponding plan view of the structural model are presented in Fig. 2.

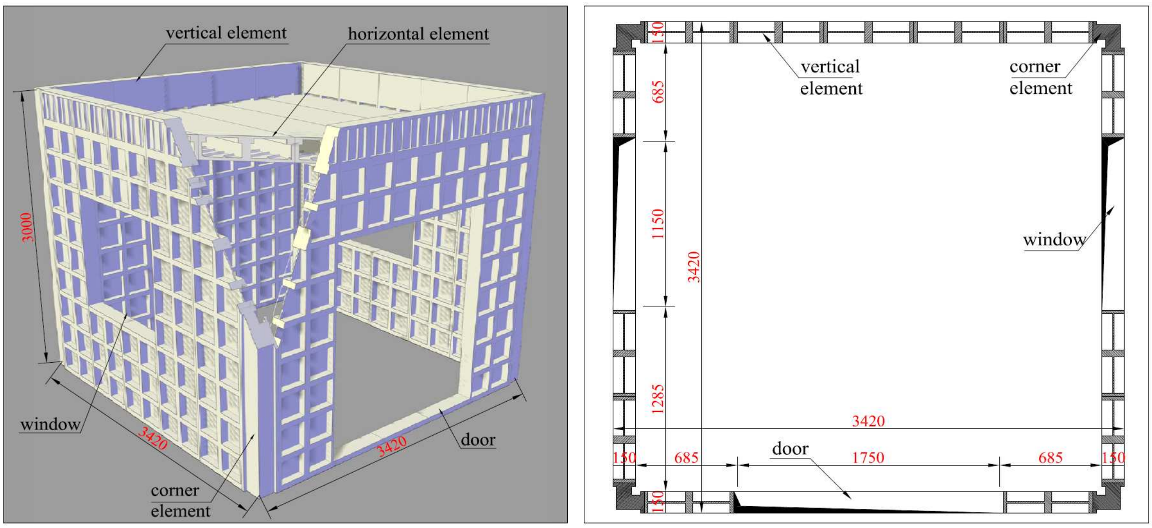


Fig. 2 Perspective and plan view of the structural tested model

Fig. 3 shows the composition of the structural elements as solution 1 presented in Fig. 1a, and the construction process for the experimental model. The material composition used for the mineral matrix has been selected as the mixture NCK 50/35/15 with 50% sand, 35% OPC and 15% eco-cement.

a b c

Fig. 3 Structural elements: a- constitutive layers; b- mounting of the model structure on the shaking table; c- cast of the fluid mineral matrix over the reinforced polystyrene panels

The model has been installed on the shaking table with the gravity load capacity of 160 kN and the action type provided triaxially (two in horizontal plane, one in vertical direction). The data acquisition during the test has been digitally performed, by simultaneously recording signals from 2 types of transducers Dytran 3202A1 LIVM (accelerometer) and PT5AV (displacement transducer).

Before the installation of the acquisition transducers the structural model has been prepared for a better visualisation of the structural GFRMMC layer. Fig. 4 presents the procedure for thermal insulation layer carrying-off.

Fig. 4 Prepared structural model with the thermal insulating layer removed

Four displacement transducers (TD) and six accelerometers (A), were installed to measure the response of the structural model during the shaking table motions. The measurement points were established to identify several basic mode shapes and related deformations. Fig. 5 shows the positions of the accelerometers at the top floor and the displacement transducers at the table level and top floor. Thus the measured displacements can show the torsion effect due to the accidental asymmetry of the modular system.

Fig. 5 The shaking table axis and the instrumentation of the structural model

Dynamic analysis. An essential step in the seismic design of structural buildings is to determine the natural frequencies of the structure [13, 14]. The GFRMMC structure has been foreseen considered as a short-period structure. Therefore, the response of the structural system to ground motion has been dominated by the fundamental frequency of the structure. In the present study, the fundamental frequency of structural model was determined based on the white noise tests performed as a first step. The fundamental frequency of the structural model was determined as 7Hz. No mass was added on top of the model.

Input motions. The dynamic loading applied to the specimen on the shaking table started from a set of diagnostic low level tests on the intact specimen including impulse loading and white noise excitation. Finally, respective low-level to high level seismic excitations were achieved. The base motion records were applied to the building progressively. The applied ground motion data is shown in table 3. The acceleration time histories were scaled to match target response spectra of 5% damping for the representative site.

Table 3. The summary of the dynamic test characteristics

Applied motion	Label	Frequency (Hz)	Duration (s)	acc. (g)	acc. (g)
Sine sweep 7Hz – cyclic loading	SS7	7	10	0.404	0.40
Vrancea 1986 -50%	VN50	1.5	25	0.50	0.48
El Centro 1940 – 50%	ELC50	4	30	0.52	0.52

Results and discussion

The model was excited progressively with peak ground acceleration (PGA) ranging from 0.1 to 0.9g. The phase-frequency relationships of acceleration responses are obtained by using transformation function and fast Fourier transformation technique. Fig. 6, 7 and 8 shows the results of frequency-spectra analysis for the acceleration responses of the top floor of the structural model.

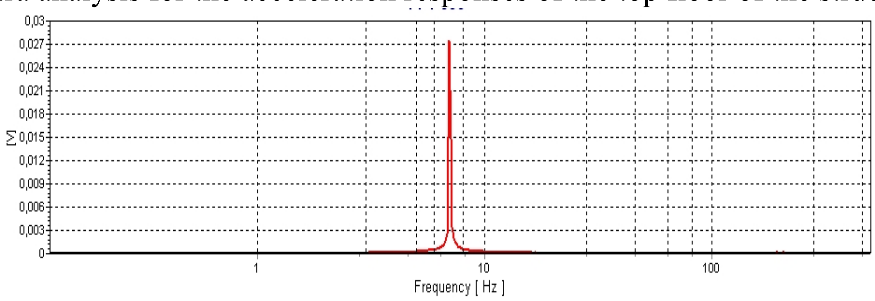


Fig. 6 Response spectra in X direction - sine sweep 7Hz action (SS7)

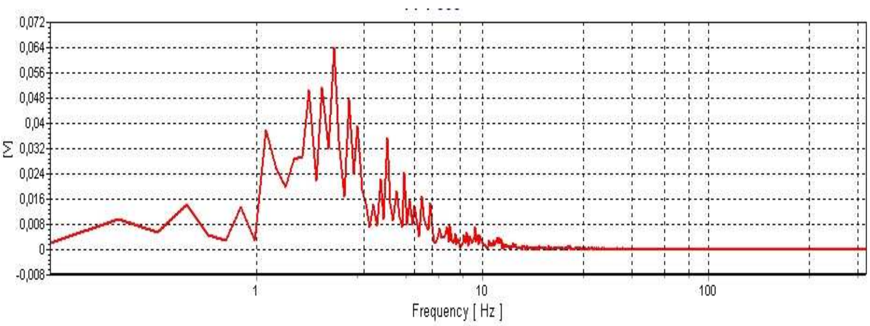


Fig. 7 Response spectra in X direction - Vrancea 1986 – 50% action (VN50)

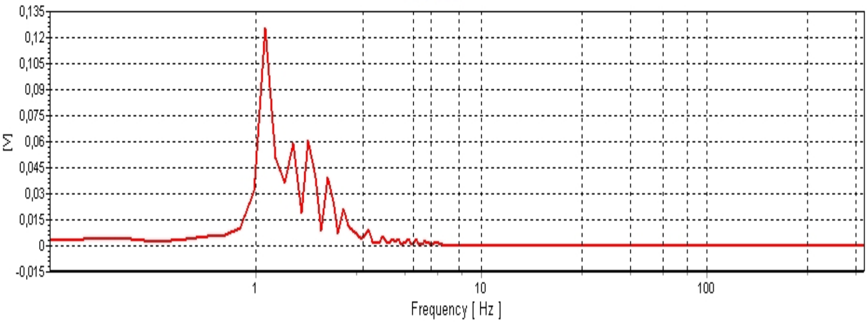
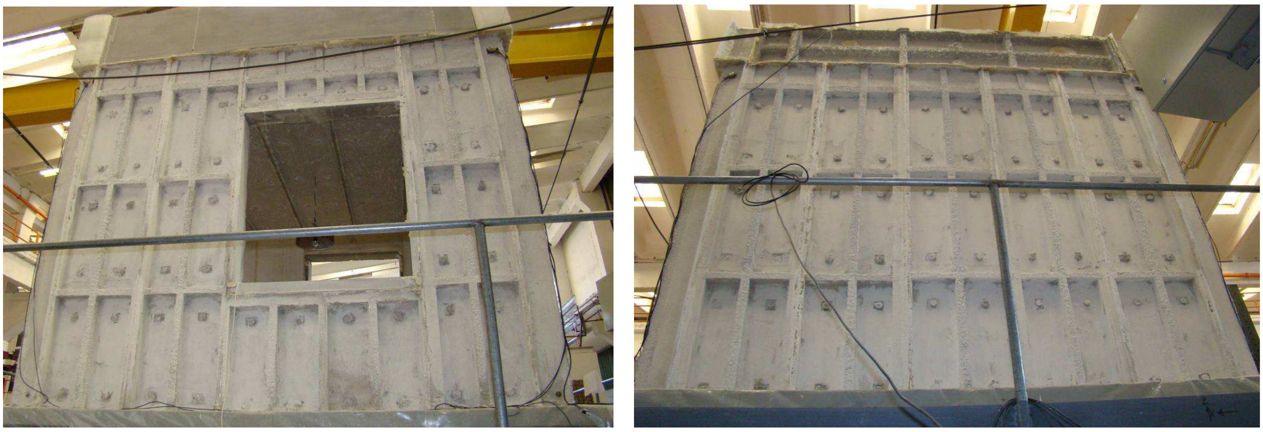


Fig. 8 Response spectra in X direction - El Centro 1940 – 50% action (ELC50)

The behaviour of the structural model was rigid due to the light weight (about 6.5 tonnes) reported to overall stiffness. After each test the initial fundamental frequency of structural model was determined but there was no significant change. Photos of the model after the shaking table test are presented in Fig. 9a and b but no visible cracks during the tests were observed. A summary of the recorded results are presented in Table 4. The model successfully resisted to repeated ground motions. Significant damages were not produced due to shaking table test.



a. b.

Fig. 9 Aspects of the exterior walls after shaking table tests: a- east side; b- south side

Table 4. The structural response in accelerations and maximum absolute displacements

Run	**Accelerations**								**Displacements**			
	A0 (g)	**A1 (g)**	**A2 (g)**	**A3 (g)**	**A4 (g)**	**A5 (g)**	**A6 (g)**	**A7 (g)**	**TD1 (mm)**	**TD2 (mm)**	**TD3 (mm)**	**TD4 (mm)**
SS7	0.51	0.48	0.49	0.52	0.47	0.46	0.47	0.49	31	30	33	34
VN 50	0.72	0.71	0.70	0.71	0.39	0.41	0.42	0.40	27	26	32	31
ELC50	0.32	0.34	0.31	0.32	0.36	0.35	0.36	0.37	42	41	47	46

Building prototypes of the structural system. After obtaining the preliminary experimental results it was decided to design and build two building prototypes as dwellings located in rural area. The first prototype Fig. 10a, used the panel system units with one centred layer of composite material and two thermal insulating layers described in Fig. 1a. The second prototype build presented in Fig. 10b, used the solution described in Fig. 1b, with two centred layers of composite material and three thermal insulating layers. Both structures have been monitored during the execution process. The entire structure has been completed in 21 days in case of the first prototypes that has extended on two stories Fig. 10a and only 11 days in case of the second prototype with one storey Fig. 10b.

a. b.

Fig. 10 The building prototypes made of mineral composite material: a- first solution system; b- second solution system

The prototype buildings immediately after completion have been monitored during service. After one year of monitoring activities, in case of the first prototype, some disadvantages were drawn: the panels have been too heavy for hand mounting, occurrence of cracks within the joints, excessive humidity and improper ventilation in the inner space; high execution costs. Compared with the first structural system developed an improved behaviour with several advantages like: reduced weight of the panels, increased dimensions of the panels, fewer joints, increased overall stiffness, simpler manufacturing process, higher thermal efficiency, better structural performance, reduced costs in terms of execution and service. Since the third structural wall solution is continuously cast in horizontal layers from bottom to top of the structure, the different executive approach eliminate the joints between panels and the possible cracks.

Conclusions

The possibility of usage in the construction field of a green mineral matrix achieved by partial replacement of the Portland cement with a binder/ eco-cement obtained from industrial waste, has been extensively studied in the research and development programs carried out at the Faculty of Civil Engineering of Iasi. The intended use direction is related to the development of a modular structural systems made of mineral matrix reinforced with fibreglass meshes as an alternative for traditional building system with masonry structures or reinforced concrete.

The efficient use of this mineral matrix composite depends on a thorough knowledge of its strength and stiffness characteristics required for the design process; therefore a comprehensive experimental program has been designed and performed. The ecological matrix and the corresponding mineral matrix composite have a good workability enabling the proper casting of the experimental samples and of the prototype components.

Besides the materials experimental tests, one storey structural model was build and tested on shaking table. The seismic behaviour monitored during the tests, showed that the modular panels system is stiff (natural frequency 7 Hz) and has a convenient loading capacity. The deteriorations of the structural elements were insignificant.

The final step in the research program was the implementation of the experimental and theoretical results in building of two prototypes. These were built and monitored during the execution and after their completion. Important observations were drawn regarding the main disadvantages and necessary adjustments of the proposed modular system. The main conclusions showed that the mineral matrix made of a recyclable binder/eco-cement in addition of the reduced amount of ordinary Portland cement can be reinforced with glass fibres mesh obtaining a mineral composite material with good structural performance for construction elements. In terms of costs, a preliminary analysis showed that these structural systems can be 35% cheaper than traditional masonry systems.

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