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RESEARCH ARTICLE

NUMERICAL SIMULATION OF TILE IMPACT BEHAVIOUR

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ABSTRACT

The lack of devices to test the tiles is not a reason to ignore the problems related to their durability. This article presents the results of an analysis of the impact behaviour of three qualities of tiles. The strike force of a fibro-mortar (TFM) is 70% lower than that of a vibrated mortar (TMV) and 54% lower than that of a baked clay (TAC) tile. Deflection results (TFM = 1.24 mm; TMV = 0.56 mm and TAC = 0.68 mm), stresses and deformations show that TFM resists better because it deforms extensively before breaking. This study shows that, compared to shocks, fibro-mortar tiles are more resistant than vibrated mortar tiles and baked clay tiles, which are more durable during operation.

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INTRODUCTION

In the regions of Africa south of the Sahara, ambient temperatures can reach high values of up to 50°C in the shade [De Backer, 1947]. This is why ceramic roofs are preferred over metal roofs (aluminum) because they provide thermal and acoustic comfort and are economical. To cover a habitat, for example, fibro-mortar (TFM), vibrated mortar (TMV) or baked clay (TAC) tiles are encouraged. The Tile in fibro - mortar consists in making a tile produced with a mortar of cement, to which small quantities of natural or synthetic fibers are added. For the vibrating mortar tile, small-diameter aggregates replace fibers [Odul, 1996]. When these tiles receive shocks from fruits or various objects, we see a large number of breaks. In general, manufacturers do not even have adequate technical equipment to test their mechanical resistance (bending, heel traction, impact or impact, sound, etc.). However, a tile subjected to an impact load may be treated as a plate or shell receiving a striking force [Bozabe, 2013]. The simple and practical numerical method proposed by this analysis makes it possible to describe and explain the behaviour of the tiles to shocks.

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The tile modeling and the simulation of its behaviour is performed by the structure calculation software Autodesk Robot Structural Analysis Professional 2016 [Peter Fritzon , 2014; -8]. Three different qualities of tiles with the same support and loading conditions were subjected to a modal dynamic analysis [8]. An experimental device (Figure 2) was used to validate the results. An interpretation of the results of the stress and deformation fields, displacement and rotations fields was carried out to better understand the tiles manufactured from the different materials.

MATERIALS AND METHODS

General configuration of impact or impact resistance (Jen-Louis Fanchon, ?; Spenle, 2003).

The static deflection Y of the tile is written:

$Y = ML^3/48EI$(1)The dynamic coefficient of impact μ on the tile is written:

$$\mu = [\frac{2H_c}{Y} x \, (1 + \frac{0{,}5M_t}{M})]^{0,5} \quad (2)$$

The F_f strike force of the M ground ball on a M_t mass tile and inertia I is written:

$$F_f = \mu . Mg \quad (3)$$

With H_c = 20 cm normative fall height
M = 200 g normative mass of the ball
L = 37 cmtile reach
I = 10, 67 cm^4moment of inertia of the tile
Emodule from Young

Principle of the impact resistance test

- The tile is laid flat on the table below the impact test device; adjust the device to a normative height of 20 cm above the table;
- 200 g normative ball is placed on the said device 20 cm above the tile;
- The ball is dropped on the tile using a joystick that is turned. The impact can cause cracks to appear or the tile to break;
- From the normative drop height Hc = 20 cm, the drop height of the ball is varied until the break of the tile or the appearance of cracks. Then the breaking height Hr: Hr = 20 cm: bad tile; 20 cm Hr = 50 cm: acceptable tile; H r > 50 cm: good tile. The sound test makes sure.

Production of experimental tiles [Yamba, 1997]

The production stages are:

Shaping to part geometry

- Placement of the mixture in the vibrating table molding frame;
- Compaction by vibration;
- Transfer of mixture to mould or mold;
- 24-hour dry mold cure under an airy shed (TFM and TMV);
- 24-hour dry cure on a sun or dryer (TAC) mold;
- Chemical reactions of cement hydration by anhydrous compounds C3S, C2S, C3A and C4AF) from cement or cement plug (TFM and TMV);
- Desiccation and Curing by Heat (TAC);
- Release and finish.

Hardening of the system

- Three-day wet cure in a two-day dry maturation basin under an aerated shed (TFM and TMV);
- Bake for three to five days in an oven at approximately 1100 °C (TAC);
- Conduct of physical and mechanical testing on tiles and recording of results.

Study of the vibration of the tile [Bathe, 1976; Chaskalovic, 2004]: Modal analysis refers to the study of free or proper vibrations of the tile. The global rigidity matrix $[K]^{Str.}$ of the tile is obtained by assembling the elementary matrices $[K]^{él.}$ expressed in the global benchmark set out in our article published in the International journal of engineering sciences and research (IJESRT) [Bozabe Renonet Karka, 2019]. The complete system expressing the behaviour at the static equilibrium of the tile is written:

$$\{F\} = [K]^{Str.} . \{U\} \quad (4)$$

With {F} : Vector representing the strike force applied to the tile.
{U} : Vector representing the amplitude of the nodal displacement field.

The relation (Peter Fritzon , 2014) constitutes a system of linear equations whose unknowns are the amplitudes of the nodal displacements or degrees of freedom and the amplitudes of the actions of links or reactions of supports. The Skyline resolution method implemented in the Autodesk Robot Structural Analysis Professional 2016 software seems the best solution for this system. Indeed, the shapes of the tiles and their type of finite element mesh triangles at three knots are simple so do not require huge machine resources. Also, to make it impossible to move the whole tile, it is necessary to support it properly. By means of the relationships (9) – (12), it is possible, according to their disturbances, to determine and exploit the different results of the displacement fields, stresses and deformations in the tiles. Assuming that the modal vibration is sinusoidal, the time parameter, noted and now operating, the displacement field is written:

$$U(t) = U\sin(\omega t + \varphi) \text{With} \omega : \text{Pulsation ean } \varphi : \text{phase} \quad (5)$$

The modal dynamic balance of the tile is then written:

$$[K]^{Str.} - \omega^2 \ [M]^{Str.} \{U\} = 0 \quad \text{with } [M]^{Str.} \text{the mass matrix} \quad (6)$$

The modal analysis of the tile consists of the resolution of the expression (6). However, this system will not admit non-zero solutions if:

$$\text{Det} \left([K]^{Str.} - \omega^2 \ [M]^{Str.} \right) = 0 \quad (7)$$

By solving the system (7) by the sub-space iteration method, w_i determine the different values of the pulsations in ωi but also the associated own modes. At the end of the modal analysis and therefore after extraction of the modes, two useful results are proposed: the participation coefficient which represents for a given mode the mass share projected in a given direction and the effective mass per mode or modal mass whose sum should coincide with the mass of the tile. This will be a criterion to verify the relevance of the modal analysis.

Moments relationships – Curvatures [Gay, 1999; Jean-Charles, 2008; Michel Cazenave, 2010].

The three relationships between M_x , M_y and M_{xy} moments and curvatures χ_x, χ_y et χ_{xy} can be grouped within a matrix expression where the flexural rigidity D of the tile appears, similar to the EI product of bending beam theory. The inverse relations connecting the curvatures to the moments give the shape that the average sheet takes when applied to it the moments.

$$\begin{Bmatrix} M_x \\ M_y \\ M_z \end{Bmatrix} = \frac{Ee^2}{12(1-\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \chi_x \\ \chi_y \\ \chi_{xy} \end{Bmatrix} D = \frac{Ee^2}{12(1-\nu^2)} \quad (8)$$

Stress Relationships – Moments [Gay, 1999; Jean-Charles, 2008; Michel Cazenave, 2010]

Similarly, normal and shear stresses can be connected to the bending and twisting moments by:

$$\sigma_{xx} = \frac{12z.M_{xx}}{e^3}\ \sigma_{yy} = \frac{12z.M_{yy}}{e^3}\ \sigma_{xy} = \frac{12z.M_{xy}}{e^3} \quad (9)$$

This gives for the extreme fibers of the tile $e = \pm\frac{e}{2}$ where the extreme values of normal and tangential stresses:

$$\sigma_{xx} = \pm\frac{6M_{xx}}{e^2}\ \sigma_{yy} = \pm\frac{6M_{yy}}{e^2}\ \sigma_{xy} = \pm\frac{6M_{xy}}{e^2} \quad (10)$$

Stress - deformation relationships [18-20]

In the case of an isotropic material, Hooke's law states:

$$\sigma_{ij} = \frac{E}{1+\upsilon}\left(\varepsilon_{ij} + \frac{\nu}{1-2\nu}\varepsilon_{kk}\delta_{ij}\right) \quad (11)$$

δ_{ij} the Kronecker symbol equal to 1 if i = j and 0 if i ≠ j

ε_{kk} the trace of the tensor of the deformations (sum of the diagonal terms of the tensor). Relationships (11) can be reversed to give relationships (12):

$$\epsilon_{ij} = \frac{1}{E}\left[(1+\nu)\sigma_{ij} - \nu\sigma_{kk}\delta_{ij}\right] \quad (12)$$

RESULTS AND DISCUSSION

When a spherical ball of mass M = 200 g is dropped in the middle of the tile at a height of 20 cm (Figure 2), the ratio (3) allows us to determine the F_f strike force on each tile quality. It turns out that the impact force of the fibro-mortar tile is low (1.21 kN) compared to the fired clay tile (2.63 kN) and the mortar-vibrated tile (4.05 kN). The fibro-mortar tile significantly reduces the striking force compared to TCA (54%) and TMV (70%). The deformation results presented in Table 5 show that for a given normative strike (corresponding to that of a 200 g ball), all three qualities of tiles have a good bearing capacity because the deformations at the impact of the tiles are less than the limit deformation of the concrete which is 3.5‰. However, the tile in vibrated mortar is less resistant to impact (3.2‰) as the fired clay tiles (1.9‰) and the fibro-mortar tile (0.7‰). With respect to normal operating conditions and impact durability, the concrete's compressive limit stress (12 MPa) is significantly exceeded for Tmvs and Tacs. While the limit arrow (0.74 mm) is exceeded for TFM. TMV and TAC seem to offer a little more of the best conditions in service than TFM.

The validation of the numerical results is made by comparison with the experimental results of the tests carried out on the Romanesque tile in vibrated mortar (TMV). From experience, when the ball drop height is gradually increased, the striking forces and dynamic deflections increase linearly: this is consistent with the type of numerical analysis considered. For a TMV tile strike force value of 4.60 kN, the calculated normal stress values are σ_{xx} = 97.09 MPa and σ_{yy} = 127.11 MPa. The dynamic deformation is then equal to ε = 3.6 ‰, value greater than the limit deformation of the concrete (3.5 ‰) which is assimilated to the fracture of the tile. By repeating the experiment with a drop height of 25 cm, one observes the appearance of cracks and a sudden rupture of the tile.

Table 1. Physical, mechanical and impact characteristics of tiles

Romanesque tiles 500x250x8	Density (kN/m3)	Tile mass (kg)	Young E module (MPa)	Poisson coefficient υ	Static deflection Y (10^{-6} m)	Dynamic striking coefficient **μ**	Striking force $\mathbf{F_f}$ (kN)
TFM	13,00	1,705	3 500	0,35	5,538	616	1,21
TMV	18,00	2,360	30 000	0,20	0,646	2067	4,05
TAC	16,00	2,098	14 000	0,45	1,385	1343	2,63

Table 2. Modal dynamic analysis results for fibro-mortar tiles

Mode	Frequency [Hz]	Pulsation [1/sec]	Masse Modal UX [%]	Masse Modal UY [%]	Masse Modal UZ [%]	Tot.mas.UX [kg]	Tot.mas.UY [kg]	Tot.mas.UZ [kg]
1	208,70	1311,30	39,25	0	1,73	1,7	1,7	1,64
2	254,01	1595,97	0,01	3,49	0,09	1,7	1,7	1,64
3	256,53	1611,84	0,85	0,02	17,64	1,7	1,7	1,64
4	294,51	1850,47	2,66	0	1,03	1,7	1,7	1,64
5	330,47	2076,42	0,22	0	27,25	1,7	1,7	1,64
6	485,44	3050,10	0	0,89	0	1,7	1,7	1,64
7	508,09	3192,43	14,49	0,01	0,02	1,7	1,7	1,64
8	536,91	3373,49	0	0,29	0	1,7	1,7	1,64
9	568,01	3568,94	0	2,14	0	1,7	1,7	1,64
10	584,68	3673,66	0,05	0	0,95	1,7	1,7	1,64

Table 3. Modal dynamic analysis results for mortar-vibrated tiles

Mode	Frequency [Hz]	Pulsation [1/sec]	Masse Modal UX [%]	Masse Modal UY [%]	Masse Modal UZ [%]	Tot.mas.UX [kg]	Tot.mas.UY [kg]	Tot.mas.UZ [kg]
1	498,67	3133,23	41,89	0	2,51	2,35	2,35	2,27
2	587,67	3692,42	0	3,49	0	2,35	2,35	2,27
3	627,39	3941,98	0,04	0	12,2	2,35	2,35	2,27
4	722,68	4540,73	1,48	0	2,83	2,35	2,35	2,27
5	812,15	5102,89	0,02	0	30,63	2,35	2,35	2,27
6	1155,73	7261,67	0	0,30	0	2,35	2,35	2,27
7	1184,96	7445,34	12,92	0	0,19	2,35	2,35	2,27
8	1319,23	8288,98	0	1,21	0	2,35	2,35	2,27
9	1389,29	8729,16	0	1,34	0	2,35	2,35	2,27
10	1408,61	8850,55	0,75	0	0,81	2,35	2,35	2,27

Table 4. Modal dynamic analysis results for baked clay tiles

Mode	Frequency [Hz]	Pulsation [1/sec]	Masse Modal UX [%]	Masse Modal UY [%]	Masse Modal UZ [%]	Tot.mas.UX [kg]	Tot.mas.UY [kg]	Tot.mas.UZ [kg]
1	379,55	2384,77	38,43	0	1,39	2,09	2,09	2,01
2	462,40	2905,35	0,06	3,45	1,08	2,09	2,09	2,01
3	463,84	2914,38	0,98	0,2	17,98	2,09	2,09	2,01
4	537,30	3375,94	3,77	0	0,34	2,09	2,09	2,01
5	593,51	3729,12	0,26	0	27,02	2,09	2,09	2,01
6	866,74	5445,89	0	0,95	0	2,09	2,09	2,01
7	922,66	5797,25	15,53	0,01	0,03	2,09	2,09	2,01
8	960,20	6033,1	0	0,28	0	2,09	2,09	2,01
9	1010,72	6350,54	0	1,8	0	2,09	2,09	2,01
10	1045,76	6570,72	0,13	0	0,79	2,09	2,09	2,01

Table 5. Summary of normal stress and strain, deflection and rotation results

Romane Tile 500 x 250 x 8 mm^3	TFM	TMV	TAC
Forces normatives de frappe F_f en kN	1,21	4,05	2,63
Constraints σ_{xx} (MPa)	19,56	85,48	59,86
Constraints σ_{yy} (MPa)	24,10	111,91	67,82
Deformations ε_{xx} (‰)	0,40	2,10	1,00
Deformations ε_{yy} (‰)	0,70	3,20	1,90
Rotations R_{XX} (rad)	0,020	0,009	0,010
Rotations R_{YY} (rad)	0,012	0,005	0,006
Dynamic deflection by simulation (mm)	1,24	0,56	0,68
Dynamic deflection per experiment (mm)	1,15	0,53	0,62
Deviations from dynamic deflection	7%	5%	9%

From this observation, the numerical analysis presented in this study also makes it possible to predict the bearing capacity of a tile, hence its validity. Since the tile is placed on the supports of the experimental device in Figure 2, the ball is dropped in the middle of the tile. A BORLEETI comparator 0.01 mm 0 - 10 mm placed under and in the middle of the tile records the dynamic deflection W (mm). It is noted that the differences between the deflections calculated after numerical simulation of the impact of the ball and the deflections measured from the comparators are less than 10%. This leads us to accept the numerical simulation results presented above. Furthermore, with regard to the results of the modal analysis of Tables 2, 3 and 4, among the ten calculated modes, it appears that mode 1 is more significant for all the qualities of the tiles studied because the mass share projected in the X direction is higher. Also, the effective mass per mode or modal mass coincides with the mass of each tile quality: this confirms the relevance of the modal analysis.

Conclusion

The results obtained show that in relation to the impact of various objects, synthetic or natural fibers have a substantial influence on the behaviour of a tile. Their presence results in a sharp decrease in the impact force, normal stresses and deformations and a significant increase in dynamic deflection. On the strength of this observation, the load bearing capacity of a fibro-mortar tile is considerably higher than that of clay tiles and cement mortar because, in case of impact, the fibro-mortar tile deforms extensively before breaking. On the other hand, during operation, the fibro-mortar tiles fail compared to the vibrating mortar and fired clay tiles, which are much more durable. Thus, this numerical analysis can validly replace an experimental study in the event of a lack of adequate shock-resistance testing devices. Finally, it recommends the tile manufacturer to be very vigilant when choosing the fibers used for the production of TFM tiles.

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