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REVIEW ARTICLE

Review on natural clay ceramic membrane: Fabrication and application in water and wastewater treatment

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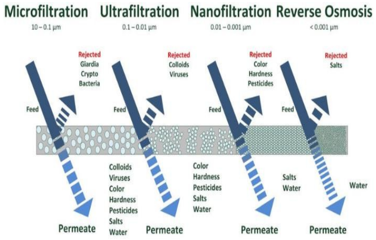
Graphical abstract



Abstract

Membrane technology is important in industrial wastewater and water treatment. Recently, the polymeric membrane technology is widely chosen in these applications. However, they are low-temperature ranges, low corrosion resistance, and low lifespan. Thus, researchers are actively trying to develop a better membrane technology such as natural clay ceramic membrane due to their excellent in chemical, mechanical and thermal resistance, high-pressure application and long lifespan. This detailed review compiles through the literature of current scientific research over the last ten years. Its highlights the key findings of factors in the fabrication of natural clay ceramic membrane that contributed to its properties. This review article presented an outline of the advantages, disadvantages, and how to overcome the disadvantages, structure, and preparation of ceramic membrane, including method, raw materials, drying and sintering temperature. The review confirmed that the sintering temperature, the composition of raw materials and pore-forming agent are significantly enhanced the mechanical strength and porosity of the natural clay ceramic membrane. However, further development and modification of the natural clay ceramic membrane technology and their applications to treat different environmental pollutants is still necessary.

Keywords: ceramic membrane, membrane technology, natural clay, water and wastewater treatment

INTRODUCTION

Nowadays, membrane technology has been widely employed in water and wastewater treatment process due to water scarcity, high water costs and stricter regulations that required more advanced water treatment technology. Most of the available membrane in the market is polymeric based membrane, and it has been widely used in membrane process industry. Polymeric membrane has a lower capital cost, scalability and good separation characteristics. However, they are low fouling resistance, low lifespan, low-temperature ranges and low corrosion resistance (Kaniganti *et al*., 2015). Opposite to ceramic membrane, can be applied in the extreme environments due to their main advantages, in excellent high chemical stability, thermal and mechanical resistance. The ceramic membrane also famous for having a longer lifespan, ease of cleaning, low dielectric constant and a low thermal conductivity (Ha *et al*., 2013; Han *et al*., 2013; Ghouil *et al*., 2015).

Ceramic membrane consisting of metal oxides such as alumina, titania, zirconia and others are most commonly applied, especially manufactured from alumina (Li, 2007; Wei *et al*., 2016). Alumina ceramic membrane is famous in its outstanding thermal, chemical and structural stability. However, it shows a drawback of high sintering temperature (a large amount of heat is required) which is above to 1500 °C to achieve good agreement between mechanical strength and porosity (Li *et al*., 2016). Besides, alumina itself is regarded as a high cost material, hence extremely expensive ceramic membrane production (Hubadillah *et al*., 2018). On the other hand, the investment cost of ceramic membrane much costs compared to the polymeric membrane. Thus, the fabrication of low cost ceramic membrane based on the natural clay (e.g. kaolino-illitic clay, smectetic clay, Moroccan pozzolan clay) was studied by several researchers due to their abundance in nature (Ali *et al*., 2018; Misrar *et al*., 2017; Achiou *et al*., 2016; Baraka *et al*., 2014). New flat ceramic microfiltration membranes were recently developed from abundant, natural materials such as natural Moroccan bentonite for industrial wastewater treatment (Bouazizi *et al*., 2016). In general, clays from bentonite materials have been applied in various industrial fields such as acts as catalysts, adsorbents and ion exchangers due to its chemical and physical properties. Bentonite materials have broad specific surface area, organic and inorganic ion adsorptive affinity, and cation exchange capability as well (Bouazizi *et al*., 2016, Roulia *et al*., 2008, Zhou *et al*., 2007; Chakir *et al*., 2002).

Focused on the water and wastewater treatment in large volume applications, the development of ceramic membrane with excellent properties and low cost are the challenging task. Thus, the main criteria to produce a high performance of ceramic membrane depends on its morphology and mechanical strength (Manohar, 2012). The properties of membrane morphologies including, pore size distribution, porosity and mechanical properties such as compressive strength and flexural strength are the main parameters that should have been considered during ceramic membrane fabrication. All these parameters depend on the type and amount of starting raw materials, additives agent, pore forming agent, sintering temperature, type of fabrication method and binder content (Bose and Das, 2014; Zheng *et al*., 2013; Sarbatly, 2011). An excellent ceramic membrane should have a good mechanical resistance to withstand high trans-membrane pressure, a high porosity to minimize the resistance to permeation which depends primarily on the sintering temperature and the raw materials used (Elomari *et al*., 2017). The first part of this article focuses on the benefits of ceramic membrane instead of a polymeric membrane. In the meantime, the disadvantages of the ceramic membrane also discovered and followed by how to overcome their disadvantages. In the second part of this reviews, the structure of single layer and multilayer ceramic membrane including their fabrication in terms of low-cost material, shaping method used, drying temperature and sintering temperature and applied to the water and wastewater treatment were described. This paper aims to provide informative and useful knowledge on the properties of natural ceramic membrane depend on their parameter elaboration for the future development of ceramic membrane.

CERAMIC MEMBRANE TECHNOLOGY

Membrane separation is a field that involves many processes. Temperature, pressure, concentration or electrical potential are the main driving forces available. Among them, pressure-driven membrane processes are most widely applied. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) are mainly the type of pressure-driven membrane process, classified based on the pore size of the membrane (He *et al*., 2019). The schematic diagrams of separations and classification of ceramic membranes are shown in Table 1 and Fig. 1, respectively.

Ceramic, nowadays, are most of the interested main materials in the fabrication of membrane instead of polymer. Ceramic based membranes, in basic, are porous and dense. The porous and dense ceramic membrane influenced by pore size, porosity of membrane and applications.

Also, most of the ceramic membranes are asymmetric composites composed in one or more different layers. The ceramic membrane structure is illustrated in Fig. 2, in terms of cross-sectional scanning electron micrograph of a support layer, followed by an intermediate layer and the top layer with small pore sizes. The support layer or known as an inner layer commonly developed as a porous support layer and provides a high mechanical strength of the membrane manufactured. This support layer also known as a single layer ceramic membrane and called it as a microporous membrane. The intermediate layer acts as a bridge between the support layer and top layer due to the difference of pore size. The top layer or called an active layer, where the separation reaction is take placed (Amin *et al*., 2016; Peng, 2008). In some cases, the improved top layer also introduced based on the applications (Gitis and Rothenberg, 2016).

Table 1 Classification of ceramic membrane (Das and Bose, 2017; Gitis and Rothenberg, 2016)

Separation process	Category	Number of layer	Average pore size	Species separation
Microfiltration	Macroporous	1 2	5 µm 0.25 µm	Bacteria, fine solids
Ultrafiltration	Mesoporous	3	100 nm	Viruses, total suspended solids, natural organic matter
Nanofiltration	Microporous	4	2 nm	Inorganics, sugars, dyes, surfactants
Reverse osmosis/gas separation	Dense	5	10 Å	Salts, metal ions, minerals

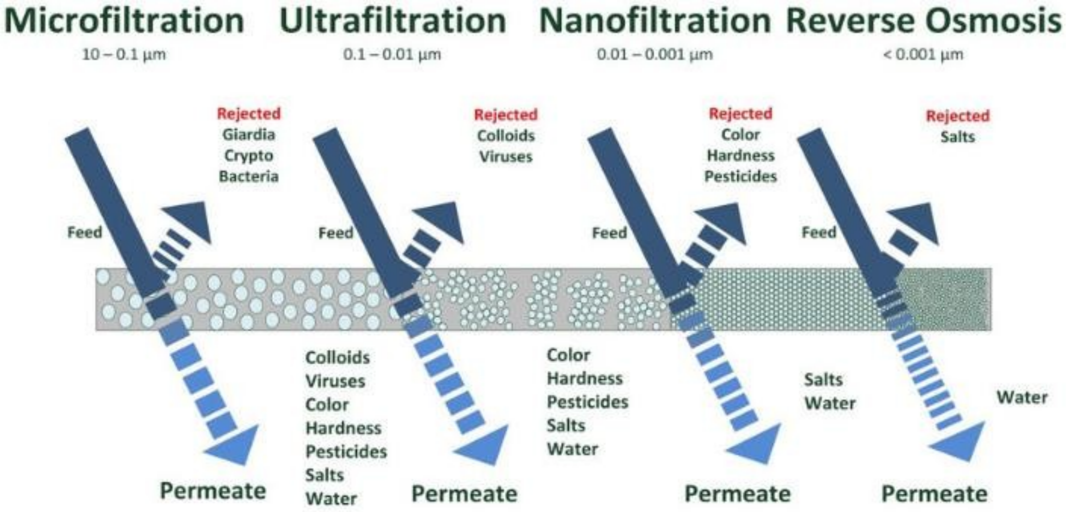


Fig. 1 Schematic diagram of ceramic membrane separation (Czarny *et al*., 2017)

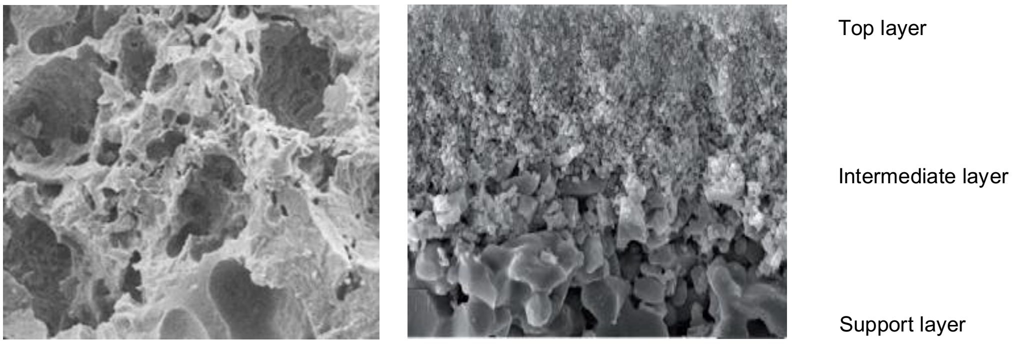


Fig. 2 Structure of a) single layer ceramic membrane (Ghouil *et al*., 2015) and b) multilayer ceramic membrane (Duscher, 2013)

Ceramic membranes are sketching a lot of interest because of their advantages such as good corrosion resistance, high thermal stability, high-pressure applications and long service life (Jana *et al*., 2011). They can work well at temperature as high as 500 °C and also can be applied in the pH range of 1 to 14 (Kumar *et al*., 2015; Benfer *et al*., 2001; Agana *et al*., 2013). The oil remaining on the ceramic membrane, for example, can be removed by thermal treatment and can withstand temperatures up to several hundred ºF (Khemakhem *et al*., 2013; AMTA, 2014). Besides, the usage of more aggressive chemical cleaning procedure could be applied to the ceramic membrane due to the durable with high chemical concentrations and chemicals characteristics. The ceramic membrane is ideal for high-temperature treatment of substances using caustic, hydrogen peroxide, chlorine, ozone and solid inorganic acid. They additionally have a decent capacity for steam cleansing (Amin, 2016). High flux rates also can be reached since ceramic membrane can tolerate high operating pressures, and this allows for extended process runs. Porous ceramic membranes also contribute to the high membrane flux (Hubadillah *et al*., 2018).

The ceramic membranes are also not degraded by the presence of bacteria or less of microbial attacks that cause degradation (Amin, 2016; Laitinen, 2002). They can be retrieved for storage, and kept dry after use. In some cases, the used ceramic membranes can be recycled as raw ceramic material to develop new elements or other products such as wallboard due to the construction materials. Thus, the cost of disposal could be reduced and also landfills issues can be overcome (AMTA, 2014).

Nowadays, the key drawbacks of ceramic membrane include a high cost of capital because of the economic aspects. These technologies are considered as economically competitive due to the availability of membranes with lower operating costs like polymeric membrane. However, ceramic membrane can overcome this problem based on the lifecycle costs such as low usage of chemicals, low backwash water frequency and high energy efficiency. For example, in the citrus industry, Sunkist Growers is a market leader in the production of over 20 million gallons of juice a year at the Tipton, California processing plant. Sunkist already uses Membralox ceramic membrane purchased from GEA Filtration since 1994 and get high-cost saving. A sales engineer of GEA Filtration, who manufactures membrane system, Mike Grigus said that about more than 40 % can reduced the amount of daily caustic usage by use reclaimed caustic. The caustic filtration system worked with the original membrane set for seven years (Bhave *et al*., 2001). Ceramic membrane also has a long lifespan. In some cases, about 20 years of warranty for ceramic membrane was offered from manufacturers. Sixteen years of ceramic membrane operation with little loss in permeability also was reported (AMTA, 2014). This means that ceramic membrane is a great filtration product.

The expensive raw materials can be replaced by cheap raw materials such as natural clay that has good potential as membrane filtration. Natural clays are in abundance and need a low firing/sintering temperature compared to the metal oxide materials like zirconia, alumina, silica and others (Khemakhem *et al*., 2009; Belibi *et al*., 2015). For example, metal oxide like alumina and zirconia as a precursor needs a higher sintering temperature, which is more than 1100 °C (Nandi *et al*., 2008; 2010) compared to the natural clay that only need around 800 to 900 °C for sintering temperature (Das *et al*., 2016; Kumar *et al*., 2015; Hristov *et al*., 2012) during fabrication. Thus, the capital cost of these membranes could be reduced efficiently.

FABRICATION OF CERAMIC MEMBRANE

The preparation of single layer or multilayer ceramic membrane could be performed in several methods such as slip casting method, tape casting method, extrusion method, dip coating method, chemical vapor deposition method and others. The configurations of ceramic membranes are able in flat sheet, tubular and multichannel models depend on the shaping method used. Fig. 3 depicts the preparation of single-layer ceramic membrane in general. Table 2 shows the elaboration of ceramic membrane in details based on literature study.

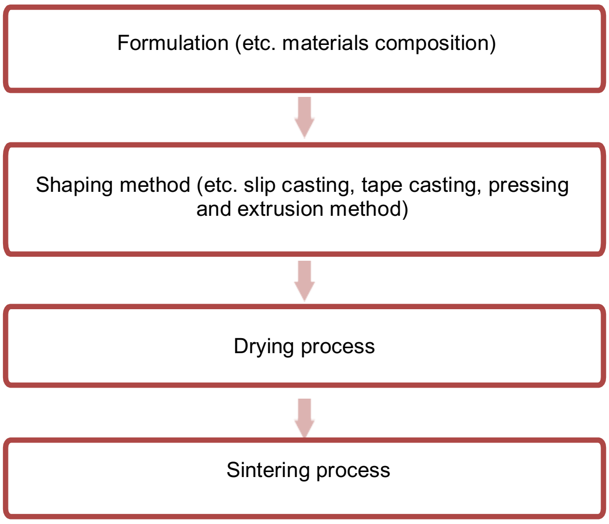


Fig. 3 General flowchart for the preparation of single layer ceramic membrane

Table 2 Preparation and elaboration of ceramic membrane

Type	Configuration	Materials	Shaping methods	Sizing (mm)	Drying temperature /time taken	Sintering temperature @ thermal cycling /time taken	Reference
Single layer ceramic membrane							
MF membrane	Cylindrical	Natural Kankara clay (different mesh of 60, 100 and 200)	3D printer	D: 30 T: 20	Between 40 and 100 °C/ 24 h	1300 °C/ 3 h	Hwa *et al.*, 2018
MF membrane	Flat disc	Natural Moroccan red clay and natural phosphate (10, 20, 40 wt %)	Uniaxial pressing	-	-	250 °C/ 4 h 450 °C/ 1 h 750 °C/ 1 h 1100 °C/ 2 h	Mouiya *et al.*, 2018
MF membrane	Flat	Natural Moroccan clay (80-100 wt %) and corn starch (0-20 wt %)	Uniaxial pressing	D: 40 T: 1.5	-	250 °C/ 2 h 750 °C/ 2 h 950 °C/ 2 h	Elomari *et al.*, 2017
MF membrane	Flat disc	Natural stevensite clay, aluminium hydroxide, silica gel, sawdust containing blends (BSB), mixtures within resin (BR) and starch containing blends (BAM)	Uniaxial pressing	D: 40 T: 3	-	1000-1200 °C/ 1-4 h	Misrar *et al.*, 2017
MF membrane	Flat	Natural bentonite (95 wt %) and starch (5 wt %)	Hydraulic pressing	-	-	250 °C/ 2 h 750 °C/ 2 h 800-1050 °C/ 2 h *the best temperature: 950 °C	Bouazizi *et al.* 2016
MF membrane	Flat	Kaolin (50 wt %), quartz (15 wt %), feldspar (10 wt %), activated carbon (10 wt %), boric acid (5 wt %), sodium metasilicate (5 wt %) and TiO_2 (5 wt %)	Casting	D: 40 T: 5	100 °C/ 24 h 250 °C/ 24 h	850, 900, 950 °C/ 6 h *the best temperature: 850 °C	Das *et al.* 2016
MF membrane	Flat	Natural Moroccan clays: clay of Meknes (CM), fine clay of Fe`s (FCF), and granular clay of Fe`s (GCF)) from northern part of Morocco	Uniaxial pressing	D: 36 T: 1.5	-	850, 950, and 1050 °C/ 2 h *the best temperature: 950 °C	Elomari *et al.* 2016
MF membrane	Flat	Natural clay (75 wt %) from Wak village, Adamawa, Cameroon and sawdust (25 wt %)	Pressing	D: 420 T: 5	Room temperature/ 24 h 100 °C/ 24 h 200 °C/ 24 h	500 °C/ 2 h 1100 °C/ 2 h	Belibi *et al.* 2015
MF membrane	Tubular	Ball clay (18 wt %), feldspar (6 wt %), kaolin (15 wt %), pyrophyllite (15 wt %), quartz (28 wt %) and calcium carbonate (18 wt %)	Extrusion	OD: 11.5 ID: 5.5 L: 100	Room temperature/ 12 h 100 °C/ 12 h 200 °C/ 12 h	950 °C/ 6 h	Kumar *et al.* 2015

MF membrane	Flat disc	Fly ash (65 wt %), calcium carbonate (20 wt %), sodium carbonate (10 wt %), boric acid (2.5 wt %) and sodium metasilicate (2.5 wt %)	Paste casting	D: 55 T: 5	-	100 °C/ 12 h 250 °C/ 2 h 800, 850, 900 and 1000 °C/ 4 h *the best temperature: 900 °C	Singh and Bulasara 2015
MF membrane	Flat disc	Clay (60 wt %), kaolinite (29 wt %), sodium carbonate (5 wt %), sodium metasilicate (3 wt %) and boric acid (3 wt %)	Paste casting	D: 55 T: 5	Room temperature/ 24 h 100 °C/ 12 h 250 °C/ 24 h	800, 850, 900, 950 °C/ 5 h *the best temperature: 800 °C	Anandkumar *et al*. 2014
MF and UF membrane	Flat	Natural Moroccan clay (region of Agadir)	Extrusion and calendaring	D: 49 T: 2	40 °C/ 24 h	800 °C/ 30 min	Baraka *et al*. 2014
MF membrane	Flat (rectangular)	Natural Sayong Ball Clay (65-100 wt %), corn starch (0-35 wt %) and ethanol as a medium	Pressing	L: 80 W: 30 T: 6.5	-	1200 °C/ 2 h	Bazin *et al*., 2014
MF membrane	Flat	Natural Sayong ball clay (55 % of the total mixture), Methacrylamide (5, 10, 15, 20 wt %), N'-Methylenebisacrylamide, 0.1 % of 1-Octanol, Ammonium Peroxodisulfate (0.1 %) and Tetramethylethylenediamine (0.05 %)	Gel casting	-	25 °C/ 2 h 60 °C/ 30 min	600 °C/ 1 h 1300 °C/ 30 min	Ahmad *et al*. 2013
MF membrane	Tubular	SM1: kaolin (40 wt %), quartz (20 wt %), feldspar (10 wt %) and sawdust (30 wt %) SM2: kaolin (40 wt %), quartz (30 wt %), feldspar (20 wt %) and sawdust (20 wt %) SM3: kaolin (30 wt %), quartz (10 wt %), feldspar (40 wt %) and sawdust (10 wt %) SM4: kaolin (40 wt %), quartz (25 wt %), feldspar (25 wt %) and sawdust (10 wt %) SM5: kaolin (50 wt %), quartz (25 wt %), and sawdust (25 wt %) SM6: kaolin (50 wt %), feldspar (25 wt %) and sawdust (25 wt %)	Pressing	OD: 50 T: 10	-	100 °C / 12 h 250 °C / 24 h 550, 700 and 850 °C / 5 h	Bose and Das, 2013
MF membrane	Flat disc	M1: kaolin (50 wt %), quartz (25 wt %), calcium carbonate (25 wt %) M2: kaolin (50 wt %), quartz (25 wt %), calcium carbonate (22 wt %), titanium dioxide (3 wt %) M3: kaolin (50 wt %), quartz (25 wt %), calcium carbonate (15 wt %), titanium dioxide (10 wt %)	Uniaxial compaction/pressing	D: 62 T: 5	110 °C/ 24 h, 200 °C/ 24 h	900 °C/ 6 h	Vasanth *et al*., 2013

MF membrane	Flat	Natural perlite powder from Tidiennit, Morocco (81.7 wt %), Methocel derived from methylcellulose (organic additives) (4 wt %) as a plasticizer, Amijel derived from starch (4 wt %) as a binder, corn starch (10 wt %) as porosity agent, PEG 1500 (Prolabo) (0.3 wt %) as a binder	Extrusion and calendaring	D: 49 T: 1.75	40 °C/ 24 h	1000 °C	Majouli *et al.* 2011
MF membrane	Flat disc	A: clay (70 wt %) and water (30 wt %) B: clay (70 wt %), sodium carbonate (3 wt %), sodium metasilicate (1.5 wt %), boric acid (1.5 wt %) and water (24 wt %)	Paste casting	D: 52 T: 6	Room temperature/ 24 h, 100 °C/ 12 h	A: 900, 950, 1000 °C/ 6 h B: 800, 900, 1000 °C/ 6 h	Jana *et al.* 2010
MF membrane	A: flat B: tubular	A: kaolin B: kaolin (80 wt %) and starch (20 wt %)	A: roll pressing B: extrusion	-	-	1000-1250 °C/ 1 h *the best temperature: 1200 °C	Bouzerara *et al.* 2009
Multilayer ceramic membrane							
MF membrane	Flat disc	SB: natural clay powder (feldspar, kaolin, pyrophyllite, ball clay, quartz and calcium carbonate) and polyvinyl alcohol (2 wt %) TL: TiO_2 nanoparticle	SB: uniaxial compaction/pressing TL: hydrothermal treatment (deposition layer)	D: 55 T: 5	SB: 100 °C/ 24 h 200 °C/ 24 h TL: 110 °C/ 12 h	SB: 950 °C/ 6 h TL: 400 °C/ 3 h	Suresh and Pugazhenthi (2017)
MF membrane	Tubular	SB: natural Texenna kaolin halloysite type (TKH) (75 wt %), calcium carbonates powder (19 wt %), Amijel as a binder (3 wt %) and Methocel as a plasticizer (3 wt %) IL: tamazert kaolin (TK) (0 wt %), polyvinyl alcohol (PVA) (30 wt %) (12 wt % aqueous solution) and water (60 wt %) TL: TKH powder (15 wt %), water (57 wt %) and PVA (28 wt %) (12 wt % aqueous solution)	SB: extrusion IL: stable suspension/colloid process (synthesis) and slip casting (deposition layer) TL: slip casting (deposition layer)	OD: 10 ID: 6 L: 200	IL: room temperature/ 12 h TL: room temperature / 24 h	SB: 1100-1250 °C/ 1 h *the best temperature: 1250 °C IL: 1150 °C / 1 h TL: 1050 °C / 1 h	Ghouil *et al.* 2015
MF membrane	Tubular	SB: clay (74 wt %), calcium carbonate (21 wt %), organic additives (2.5 wt % of Amijel derived from methylcellulose, 2.5 wt % of methocel derived from starch TL: 10 wt % of ZrO_2, 30 wt % of PVA (12 wt % aqueous solution) and water (60 wt %)	SB: extrusion TL: slip casting (deposition layer)	-	SB: room temperature/ 24 h	SB: 1150-1300 °C/ 60 min *acceptable: 1150-1250 °C TL: 1050 °C/ 1 h	Bouzerara *et al.* 2012
MF membrane	Tubular	SB: natural perlite powder from Tidiennit, Morocco (81.7 wt %), Methocel derived from methylcellulose (organic additives) (4 wt %) as a plasticizer, Amijel derived from starch (4 wt %) as a binder, corn starch (10 wt %)	SB: extrusion TL: suspended powder (synthesis) and slip casting (deposition layer)	-	SB: 40 °C/ 24 h	SB: 1000 TL: 930 °C/ 1 h	Majouli *et al.* 2012

UF membrane	Flat disc	SB: clay (70 wt %), kaolin (18 wt %), sodium carbonate (6 wt %), sodium metasilicate (3 wt %) and boric acid (3 wt %) TL: chitosan solution + 0.12 % (v/v) glutaraldehyde solution in 1:1 ratio	SB: paste casting TL: dip-coating (deposition layer)	D: 50 T: 5	SB: room temperature/ 24 h, 100 °C/ 12 h TL: 100 °C/6 h	SB: 1000 °C/ 6 h	Jana *et al.* 2011

Notes: UF: ultrafiltration membrane; MF: microfiltration membrane; SB: support body; IL: intermediate layer; TL: top player; D: diameter; OD: outer diameter; ID: inner diameter; T: thickness; L: length; W: width

Slip casting

Slip casting method is commonly used in the fabrication of pottery for a complex shape which is irregular and non- concentric as shown in Fig. 4. This method was first used in France, 1790 by Monsieur Tendelle in conjunction with the porcelain fabricating. In the ceramic membrane fabrication, slip casting method commonly used due to their simple technique and cheaper than other techniques (Hubadillah *et al*., 2018). In the process, a slurry (the mixture or solution in slip casting) is poured onto a microporous plaster of Paris (POP) mold. The porous nature of the mold gives a capillary suction pressure, which draws the fluid from the slurry into the mold as depicted by Darcy's law. A consolidated layer of solid or also known as a cast, forms on the walls of the mold (Fig. 4). After proper cast thickness is created, the excess slip is poured out and the mold and cast are left to dry. The cast contracts typically during drying from the mold and can be easily removed. When dried completely, the cast is heated to burn the binder out and sintered to produce the final product (Rahaman, 2003). However, the ratio of powder mixture and water used should be exact composition to prepare a slurry to achieve a required final product. This method often requires a long casting time, as it involves a slow drying process. In addition, the wall thickness is difficult to control during the consolidation of the drying stage, and is usually thick. The thickness of ceramic membrane using slip casting method was, as stated by Li (2007), depending on the casting time and slurry condition. The Material composition used in the slip casting method is described in Table 3.

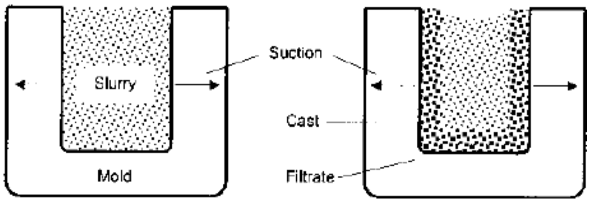


Fig. 4 Schematic diagram of the slip casting process (Rahaman, 2003)

Table 3 Composition of mixture in the slip casting technique (Rahaman, 2003)

No.	Product	Materials used (concentration, vol %)
1	Alumina	Alumina (40-50) Water (50-60) Ammoniul polyacrylate as dispersant (0.5-2) Ammonium alginate or methyl cellulose as binder (0-0.5)
2	Whiteware	Clay, silica, feldspar (45-50) Sodium silicate, polyacrylate or lignosulfate as dispersant (< 0.5) Calcium carbonate as flocculant (< 0.1)

Extrusion

Extrusion method is widely employed in the manufacturing of ceramic floor, wall tiles, clay pipes and, clay blocks and bricks. A powder mixture is compacted and formed using an extrusion process by pushing it through a nozzle in a screw/auger extruder or piston/ram extruder. The piston extruder is easy to use and consists of a piston, a tube, and a die. Although the auger extruder is a more complex design than the ram extruder as defined in Fig. 5. This extruder must ensure that the powder and other additives are homogeneous and produce adequate pressure to transfer the mixture to the die. The shaping of the final product is achieved at the die (Rahaman, 2003). However, in basic, extrusion method is applied in the ceramic membrane fabrication for obtained a tubular shape only. Only this method offers a strong membrane structure; this method requires a complicated process of preparation and also need to produce adequate pressure to move the mixture (Hubadillah, 2015).

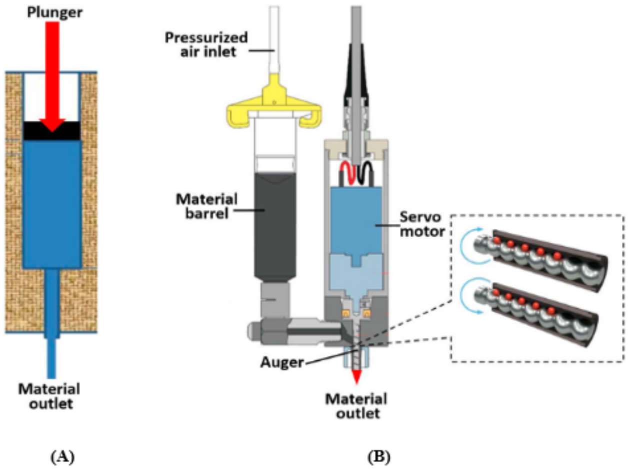


Fig. 5 Schematic diagram of type of extruder: A) ram extruder and B) auger extruder (Li *et al*., 2017)

Pressing

Pressing method is one of the most widely used in the ceramics industry. Uniaxial die pressing and isostatic pressing widely used for dry powder compaction (contain <2 wt % water), and semidry powders (hold ~5-20 wt % water). In uniaxial die compaction, the powder material undergoes simultaneous uniaxial compaction and shaping in a rigid die (Rahaman, 2003). Uniaxial die compaction process can be categorized into two processes which are, cold (Fig. 6) and hot process. A die is filled with a mixture of powder material, which is then uniaxially pressed to a green body (compacted powder) for cold pressing process. Then remove the sample. The hot process is almost similar to the cold process; however, induction under vacuum or inert gas atmosphere heats the green body (Suarez *et al*., 2016). Pressing process provided more coverage for the manufacture of ceramic membrane as compared with slip casting method.Pressing method could produce the ceramic membrane with high mechanical strength, thus, could apply in the high-pressure applications. However, the configuration made by a pressing method normally in a disc or rectangular shape only, therefore, produce symmetrical membrane rather than asymmetrical membrane. Ceramic membrane manufacture by pressing method often demanded high costs (Hubadillah, 2015).

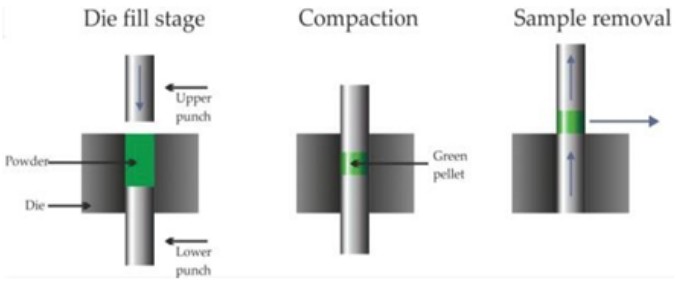


Fig. 6 Schematic diagram of uniaxial die compaction for cold process (Suarez *et al*., 2016)

Injection molding

Injection molding is a method to fabricate small components of complicated geometries and low wall thicknesses in large quantities. In basic, injection-molded components are cores for metal thread guides, casting, welding nozzles, cutting gear, and turbocharger rotors. Ceramic powders with plasticizers, binders and lubricants are homogenized to plastify the feeds, which is done in heatable mixers or kneaders above the melting point of the additives. The homogenized feed with up to 50 vol % of additives is cooled and granulated concurrently through the screws. This granulate is fed through the filling hopper to the heated injection nozzle of the injection molding machine. Fig. 7 shows the schematic diagram of screw type injection molding machine (Heinrich and Gomes, 2015). In this method, binders play a vital role within the overall fabrication route; however, the choice of a kind of binders is important to the success of the injection molding method. A good binder should have desirable chemical, rheological and debinding characteristics. In addition, it should possess several qualities for fabricating such as low cost and environmental friendly. The ratio of powder to binder is also a key parameter for successful injection molding. Insufficient amount of binder results in a high viscosity and to the formation of trapped air pockets, each of that create molding difficult. On the other hand, an excessive amount of binder results in microstructural heterogeneities in the molded product (Rahaman, 2003).

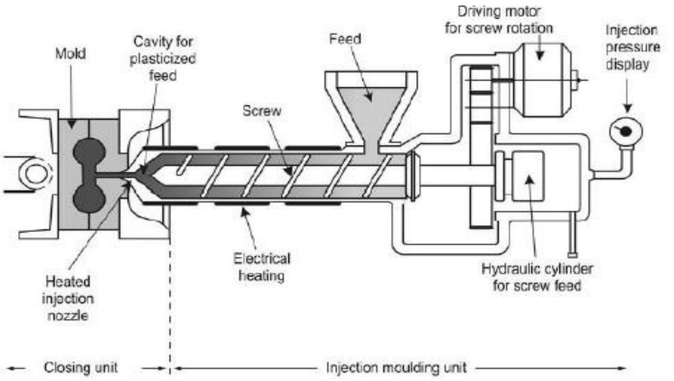


Fig. 7 schematic diagram of injection molding machine: screw type (Heinrich and Gomes, 2015)

FACTORS AFFECTING CERAMIC MEMBRANE PROPERTIES

The properties of ceramic membrane obtained, generally, depend on their parameter elaboration. The elaboration of ceramic membrane, however, should be concerned on the type of raw materials used, sintering temperature, pore former content and additive agents as a main factor that contribute to the mechanical properties, such as strength and hardness as well as shrinkage, porosity, density and water absorption of ceramic membrane as described in Table 4. Among these factors, the addition of pore former in the composition of the membrane increases porosity and permeability (Elomari *et al*. 2017). Porosity is defined as a porous substance, as the volume of emptiness can be indicated (Youmouse *et al*., 2017). As Obada *et al*. (2016) reported, the porosity of the ceramic bodies increased as a percentage of pore-forming agent applied increased. Numerous materials have been applied as a pore former, such as potato starch and sago starch (Jamaludin *et al*., 2014; Lorente-ayza *et al*., 2015), rice bran (Mahmudul *et al*., 2011; Lorente-ayza *et al*., 2015), sawdust (Bose and Das, 2015), or even in pure substances like urea (Vijayan *et al*., 2013). However, the higher percentage of pore former used caused the body strength decreased and shrinkage behavior increased. On the other hand, the higher porosity resulting from the rise in the percentage of pore former makes the membrane less mechanically robust as well as sample size significantly decreased. The shrinkage phenomenon might be occurred due to the burn out of the pore former and losses of moisture during sintering process. The shrinkage had increased as the percentage of pore former used is increased. For zero percentage of pore former content, the shrinkage occurs mainly due to the losses of moisture (Bazin *et al*., 2014). In the meantime, the density of the membrane is also decreased as the pore former content is increase. The drop in density value is caused by the elimination of pore formation. While, the ceramic membrane's mechanical strength also depends on the existence of pores-like defects that act as stress concentration (Chandradass *et al*., 2009). The presence of closed and open pores may reduce the membrane strength (Bazin *et al*., 2014). In Obada *et al*. (2017) report, they propose a compromise to obtain a high porosity, high mechanical strength macro-porous support ceramic membrane. Therefore, the sintering temperature had to be increased in order to gain greater mechanical strength. However, it should be noted that due to the transformation of the clay and the formation of the glassy phase, porosity decreases with temperature. On the other hand, the mechanical strength increases with the temperature induced by the transformation of the clay and the presence at high temperature of the glassy layer.

Therefore, sintering temperature plays the main parameter to the properties of ceramic membrane through alteration of the microstructure, included mechanical strength (Denry and Kelly, 2008; Fan *et al*., 2017). The sintering process is where the consolidation step or densification of granular compact is performed by heat action with a high temperature below the melting point of the main constituent, in order to accelerate its strength by bonding the particles together. Whether by dry pressing or slip casting method, after the initial molding of the ceramic it is still necessary to densify the green bodies to create a continuous 3D structure and therefore to produce ceramic pieces acceptable for the chosen application. For example, Guo *et al*. (2015) focused on the intensity of Al_2O_3-ZrO_2 composites affected by the different sintering temperatures. They found that the compressive intensity usually increased with the increased sintering temperature (from 1400 °C to 1500 °C) (Al_2O_3:ZrO_2 = 7:3) (Fan *et al*., 2017). Similar to Mohtor *et al*. (2017a), there was a pattern of increase in mechanical strength in the manufacture of kaolin hollow fibre membrane with the rise in sintering temperature. This phenomenon could be described by the grain production of ceramic particles that took place during the sintering process, resulting in the creation of bonds between the ceramic particles that strengthened the mechanical strength of the membrane. Thus, a higher sintering temperature may lead to the formation of further bonds between the ceramic particles, which would reinforce the membrane. So, a higher sintering temperature could contribute to the creation of more bonds between the ceramic particles, resulting in membrane strengthening. Liu and Li (2003) also stated that the sintering temperature had a significant impact on the membrane's mechanical strength due to the need for the ceramic particles to fuse and bond properly. Hence, they clarified that the sintering temperature should be selected at about three-fourths of the material's melting point during membrane manufacture. However, the higher sintering temperature applied, caused increased body densification and shrinkage, and contributed to water flux output and reduced or entirely deformed porosity. As reported by Mohtor *et al*. (2017b), reductions in porous structure across the membrane were observed when higher sintering temperature were applied, which was greatly affected by the shrinking pores and membrane densification. In addition, a good compromise should be found between the sintering temperature and the former pore percentage to produce a high water flow, high mechanical strength and high ceramic membrane porosity.

Besides, an additive agent such as binder, which is also used in the manufacture of ceramic membranes to give the ceramic membrane strength by creating bridges between particles. This also provides plasticity in some situations, as well as assists in the process of body formation and is usually eliminated as completely as possible during the sintering steps (Jamaludin *et al*., 2014; Das, 2011). As shown in the Mohtor *et al*. (2017b) study, the kaolin hollow fibre precursor has still not been sintered, and the presence of dispersant and polymer binder in the kaolin hollow fibre precursor could be strongly detected from the SEM images. After done sintering temperature at 1200 °C, there is no binder and dispersant showed. However, at this temperature, the sintering process of the kaolin hollow fibre membrane is starting to take place based on the shape of the neck between the contact grains. In addition, at high binder contents, particles appear to stay close to each other or increase the interconnection between particles-particles reduces the voids in the membrane support, resulting in a decrease in porosity and increased strength (Bose and Das, 2014). However, the high amount of binder in ceramic manufacture (above 40 %) was harmful to the mechanical strength of the resulting clay-alumina supports. This may be due to the creation of pores and the relation between particles is distant because the binder burns off during the sintering process (Oun *et al*., 2017). Thus, the optimum amount of binder should be applied in order to ensure good adhesion and uniformity of the ceramic structure associated with rheological properties is achieved. In addition, Zhang *et al*., (2006) concluded that, at the liquid state, polymer binder could better maximize the efficiency of alumina support compared to the solid-state. Often, that the amount of its use directly influences the support efficiency including porosity, pore size distribution and binding strength.

The types of raw material also influence the properties of ceramic membrane. For example, Kitouni and Harabi (2011) focus on porcelain making using local quartz, potassic feldspar (PF) and kaolin raw materials. All these deposits of raw materials in Algeria, i) quartz from the El Oued region, ii) PF from the deposit of Ain Barbar (Annaba region), and iii) kaolin from the deposit of Debagh (Guelma area). Based on the flexural strength result, these manufactured membranes were achieved a higher strength, which is about 197 MPa at sintering temperature of 1200 °C for 2 h holding time compared to the commercial porcelain, only about 60 and 80 MPa. In addition, Elomari *et al*. (2016) study different natural Moroccan clay on the fabrication of ceramic membrane, which is, collected from different location of northern part of Morocco; 1) clay of Meknes (CM), 2) fine clay of Fe's (FCF) and 3) granular clay of Fe's (GCF). All these manufactured membranes fabricated using uniaxial pressing method and sintered at 950 °C for 2 h. The result obtained is all manufactured membrane shows a different porosity and mechanical strength depend on their type of clay. The porosity of CM, FCF and GCF are 28.1 %, 30.8 % and 40.0 %, respectively; and the mechanical strength is 14.8 MPa, 16.13 MPa and 14.42 MPa, respectively. This might occur due to the chemical composition of the clay itself. In facts, different of raw materials used as precursors applied a different of condition preparation (etc. sintering temperature, sintering time) was creating the different types of stability, morphology and porous texture of ceramic membrane as well as contributes to the mechanical strength (Jana *et al*., 2011).

APPLICATION OF CERAMIC MEMBRANE IN THE WATER AND WASTEWATER TREATMENT

The successful of ceramic membrane in many industrial applications, such as the application of microfiltration in the bacteria removal from food and dairy products (Tomasula *et al*., 2011), juice clarification (Nandi *et al*., 2009), hot gas filtration (Li *et al*., 2011) and the filtration of fermentation broths in the biotechnology and pharmaceutical applications (Waszak and Gryta, 2016) nowadays, attracts much attention in the membrane technology development. Also, ceramic membrane has become a great interest to be the alternative treatment of the wastewater included, pollution treatment from industrial area; separation of oily wastewater (Madaeni *et al*., 2012; Fazullin *et al*., 2015), removal of heavy metal content in industrial effluent (Noor *et al*., 2017) and treatment of textile mill (Barredo-Damas *et al*., 2012). Table 5 summarizes some applications of ceramic membrane in the water and wastewater treatment based on type of membrane, commercial or fabricated membrane and main material used either natural or commercial clay.

Several studies investigating the ceramic membrane have been carried out on the application of industrial wastewater (Noor *et al*., 2017; Ebrahimi *et al*., 2016; Almandoz *et al*., 2015). A recent study by Noor *et al*. (2017) elaborated the ceramic membrane filtration based on Sayong ball clay which is obtained from Sayong District in Perak State, Malaysia, for nickel removal from industrial wastewater. Around 82 % to 89 % of nickel was efficiently rejected. Ebrahimi et al. (2016) conducted a study that focused on potential applications of ceramic membranes in the pulp and paper industry for the treatment of bleach plant effluent. In this study, semi and series batch membrane processes consisting of microfiltration (MF), ultrafiltration (UF) and nanofiltration (NF) ceramic membranes were designed to remove residual lignin from effluent and reduce the chemical oxygen demand (COD) during production of sulfite pulp. The two-stage process of MF and followed by UF (both filtration prepared using ceramic membrane) gave good performance of separation and efficient for the alkaline bleaching effluent treatment. In addition, these processes also reduced residual lignins and COD concentration greater than 70 % and 35 %, respectively. Almandoz *et al*. (2015) study on ceramic membrane from natural alumino silicates as principal components (clay, feldspar, quartz, bentonite, and alumina) due to the low price and locally produced. The performance of manufactured membrane was tested with different substances from food industry, i) goat milk pasteurization and ii) slaughterhouse wastewater treatment. The excellent results have been achieved with about 87-99 % of bacterial removal and 100 % of insoluble residue rejections; make these ceramic membranes suitable for microfiltration processes application. This shows that natural clay has a significant potential to become a great ceramic membrane filtration due to their low price and good performance.

In the household water treatment application, Fatimah *et al*. (2015) described the development and characterization of new TiO_2-modified kaolinite ceramic membrane, which is prepared using natural kaolinite with the tubular support configuration. Different composition of TiO_2 was coated on the ceramic surface was study. The manufactured membrane then, applied in the analysis of bacteria content, ferum (Fe), manganese (Mn), nitrate (NO^-) total dissolved solid (TDS) and total suspended solid (TSS) before and after filtration. It has conclusively been shown that there is significantly affected in Fe, Mn, NO^- and bacteria reduction, while COD, TSS and TDS are not significantly affected. Similarly, Ajayi and Lamidi (2015) studies on the heavy metal (zinc (Zn), nickel (Ni), manganese (Mn), lead (Pb), chromium (Cr), copper (Cu)) and physicochemical parameter (etc. hardness, turbidity, conductivity, TDS, pH) in-home use water using ball clay as the main precursor for ceramic water filters. Their manufacturer ceramic membrane shows an excellent result with all the parameters studies is significant reduction.

In the oily wastewater treatment, the study by Abbasi *et al*. (2012) had fabricated the tubular mullite ceramic microfiltration membrane from kaolin clay, obtained from the Zenooz mine in Marand, Iran. According to the obtained result, about more than 94% of total organic carbon rejection for synthetic feeds was achieved. Similar to Nandi *et al*. (2010) had treated oily wastewater using low-cost ceramic membrane that has been prepared from inorganic precursors such as quartz, kaolin, feldspar, sodium carbonate, sodium metasilicate and boric acid. At 150 mg/L feed oil concentration (ΔP = 206.8 kPa), 15.05×10^{-6} m^3/m^2s of permeate flux and 98.51 % of rejection efficiency was observed.

FUTURE PERSPECTIVE

Development of membrane technology to the industry is dependent on its performance as well as its cost. The ceramic membrane more focused nowadays in the scientific research world compared to the polymeric membrane due to its benefits. However, the big issue of ceramic membrane having a high fabrication cost. Therefore, comprehensive studies leading to the benefits of ceramic membrane in terms of long service lifespan and better performance will definitely a more focused in future to compensate for the high cost. On the other hand, other alternatives also should be focused such as on the fabrication cost of ceramic membrane. It can be realized by the selection of raw materials and method used. For example, natural clay or solid waste or any cheap materials can be used as the main material in the fabrication of ceramic membrane as well as in terms of method. Most of the researcher use the pressing method. This method is expensive compared to the other method. Slip casting method offers an excellence method where is cheap, no complicated technique and no assistance of high technology machinery needed. However, the thickness of ceramic membrane using slip casting method was depending on the casting time and slurry condition and also challenging to control. Thus, a modified slip casting technique should be introduced to overcome this problem. In addition, the performance of ceramic membrane should be focused and this strongly connected to the factor contributing in the production of effective low-cost ceramic membranes. However, further investigation such as optimization of composition and size of precursor materials and pore formers through the design of experiment (DOE) is necessary to improve the development and properties of the ceramic membrane.

Table 4 Fabrication parameters and properties of ceramic membrane

Fabrication parameter			**Properties**						**Reference**
Materials and compositions	**Shaping methods (configuration)**	**Sintering temperature /time taken**	**Pore Diameter (μm)**	**Shrinkage (%)**	**Density (%)**	**Porosity (%)**	**Water absorption (%)**	**Mechanical strength (MPa)**	
Natural bentonite from Nador, Morocco (95 wt %) and starch (5 wt %)	hydraulic pressing (flat)	950 °C/ 2 h	1.70	7.5	-	32.12	14.33	22	Bouazizi *et al*., 2017
Kaolin (40 wt %) + PES (5 wt %) + NMP (54 wt %) + Arlacel P135 (1 wt %)	Extrusion (hollow fibre)	1200 °C/ 5 h 1300 °C/ 5 h 1400 °C/ 5 h 1500 °C/ 5 h	1200 °C:0.58 1300 °C: 0.51 1400 °C: 0.49 1500 °C: 0.45	-	-	-	-	1200 °C: 5 1300 °C: 33 1400 °C: 70 1500 °C: 127	Mohtor *et al*., 2017b
Kaolin clay (25 wt%), alumina (75 wt%), binder (methocel, 6 g) and water (30 g)	Extrusion (tubular)	1350 °C/ 90 min	0.75	-	-	48	-	37	Oun *et al*., 2017
Natural Moroccan Pozzolan (different Moroccan pozzolans (Pozzolan of N'Aid Said (PN), Black Pozzolan of Hebri (BPH) and Red Pozzolan of Hebri (RPH) from Central middle atlas)	Hydraulic uniaxial pressing (flat disc)	950 °C/ 2 h	PN: 2.84 BPH: 2.20 RPH: 2.36	PN: 2.14 BPH: 4.95 RPH: 2.17	PN: 2.1 BPH: 2.1 RPH: 2.1	PN:32.4 BPH: 29.6 RPH: 33.0	PN: 14.6 BPH: 12.8 RPH: 15.2	PN: 14.8 BPH: 18.58 RPH: 19.16	Achiou *et al*., 2016
Kaolin (50 wt %), quartz (15 wt %), feldspar (10 wt %), activated carbon (10 wt %), boric acid (5 wt %), sodium metasilicate (5 wt %) and TiO_2 (5 wt %)	Casting (flat disc)	850 °C/ 6 h 900 °C/ 6 h 950 °C/ 6 h	850°C: 1.55 900°C: 1.78 950°C: 2.65	-	-	850 °C: 18.88 900 °C: 5.59 950 °C: 2.25	-	-	Das *et al*., 2016
Natural Moroccan clays: clay of Meknes (CM), fine clay of Fe`s (FCF), and granular clay of Fe`s (GCF)) from northern part of Morocco	Uniaxial pressing (flat)	950 °C/ 2 h	CM: 1.8 FCF: 1.50 GCF: 2.84	CM: 5.26 FCF: 2.5 GCF: 3	-	CM: 28.1 FCF: 30.8 GCF: 40	-	CM: 14.80 FCF: 16.13 GCF: 14.42	Elomari *et al*., 2016
Natural clay (75 wt %) from Wak village, Adamawa, Cameroon and sawdust (25 wt %)	Pressing (flat disc)	1100 °C/ 2 h	-	-	-	42	-	-	Belibi *et al*., 2015

Natural Texenna kaolin halloysite type (TKH, 75 wt %), calcium carbonates powder (19 wt %), Amijel as a binder (3 wt %) and Methocel as a plasticizer (3 wt %)	SB: extrusion (tubular)	1250 °C/ 1 h	SB: 8	-	-	47	-	40	Ghouil *et al.*, 2015
Ball clay (18 wt %), feldspar (6 wt %), kaolin (15 wt %), pyrophyllite (15 wt %), quartz (28 wt %) and calcium carbonate (18 wt %)	Extrusion (tubular)	950 °C/ 6 h	0.309	-	-	53	-	12	Kumar *et al.*, 2015
M1: kaolin (50 wt %), quartz (25 wt %), calcium carbonate (25 wt %) M2: kaolin (50 wt %), quartz (25 wt %), calcium carbonate (22 wt %), titanium dioxide (3 wt %) M3: kaolin (50 wt %), quartz (25 wt %), calcium carbonate (15 wt %), titanium dioxide (10 wt %)	Uniaxial compaction method (flat disc)	900 °C/ 6 h	M1: 1.30 M2: 1.06 M3: 0.45	-	-	M1: 30 M2: 26 M3: 23	-	M1: 34 M2: 12 M3: 10	Vasanth *et al.*, 2013
Natural zeolite from Kralevo, Haskovo region, Bulgaria IL: zeolite powder	Semi-dry pressing (flat disc)	800 °C 850 °C 900 °C 1000 °C	-	800 °C: 5.0 850 °C: 10.0 900 °C: 18.0 1000 °C: 22.5	800 °C: 1.48 850 °C: 1.59 900 °C: 1.86 1000 °C: 2.1	800 °C: 38 850 °C: 30 900 °C: 13.39 1000 °C: 0	800 °C: 30.00 850 °C: 20.12 900 °C: 7.20 1000 °C: 0	800 °C: 4.5 850 °C: 5.0 900 °C: 6.0 1000 °C: 6.5	Hristov *et al.*, 2012
Natural perlite powder from Tidiennit, Morocco (81.7 wt %), Methocel derived from methylcellulose (organic additives) (4 wt %) as a plasticizer, Amijel derived from starch (4 wt %) as a binder, corn starch (10 wt %) as porosity agent, PEG 1500 (Prolabo) (0.3 wt %) as a binder	Extrusion and calendaring (flat)	1000 °C	6.64	-	-	41.8	-	1.2	Majouli *et al.*, 2011
Kaolin and water (40-45 wt %)	Extrusion (tubular)	1150 °C	0.9	8.12	-	-	19.8	-	Ezziane *et al.*, 2010
Clay (81.7 wt %), Amidon (10 wt %), Methocel (4 wt %) Amijel (4 wt %) and PEG1500 (0.3 wt %)	Extrusion (tubular)	1200 °C/ 1 h	10.6	-	-	31.6	-	15	Saffaj *et al.*, 2010

Natural apatite powder from Metlaoui in the south of Tunisia (84 wt %), methocel (2.5 wt %), amijel (2.5 wt %), starch (9 wt %) and PEG (2 wt %)	Extrusion (tubular)	1160 °C	6	-	-	48	-	14	Masmoudi *et al.*, 2007

Table 5 Type of membrane used with their applications in the water and wastewater treatment

Type of membrane	Layer of membrane	Application	References
Commercial ceramic membrane			
Microfiltration membrane	Multilayer	Synthetic dye filtration (Cationic: Methyl Green and Neutral Red; and anionic: Reactive Black 5)	Chougui *et al*. (2019)
Ultrafiltration membrane	Multilayer	Synthetic produced water containing the cationic surfactant Dodecyltrimethylammonium bromide (DTAB)	Weschenfelder *et al.* (2019)
Ultrafiltration membrane	Multilayer	Synthetic dye filtration (Reactive Blue KN-R, Reactive Black 5, Reactive Red-H E7B, NaCl, and Na_2SO_4 in water solution)	Ma *et al*. (2017)
Nanofiltration membrane	Multilayer	Synthetic dye filtration (Rhodamine-B)	Yadav *et al*. (2017)
Ultrafiltration membrane	Multilayer	Synthetic dye pollutant (Methylene Blue and Methyl Orange)	Athanasekou *et al*. (2015)
Nanofiltration membrane	Multilayer	Synthetic dye filtration (textile Industries reactive, disperse, acidic and direct in blue and red)	Kishore and Kamala (2015)
Ultrafiltration membrane	Multilayer	Wastewater from beverage production	Agana *et al*. (2013)
Ultrafiltration membrane	Multilayer	Synthetic dye filtration (Reactive Black 5)	Alventosa-deLara *et al*. (2012)
Ultrafiltration membranes	Multilayer	Textile mills effluents	Barredo-Damas *et al*. (2012)
Microfiltration membrane	Single layer	Treatment of oily wastewater produced by petrochemical and oil industry	Madaeni *et al*. (2012)
Ultrafiltration membrane	Multilayer	Synthetic dye filtration (Methyl Orange, Indigo Carmine, Amido Black, Titan Yellow, Direct Green, Direct Blue and Direct Black)	Majewska-Nowak and J. Kawiecka-Skowron (2011)
Fabricated ceramic membrane: commercial clay			
Microfiltration membrane	Single layer	Oily wastewater	Rasouli *et al*. (2019)
Ultrafiltration membrane	Multilayer	Synthetic dye filtration (Alizarin Red)	Oun *et al*. (2017)
Microfiltration membrane	Single layer	Industrial wastewater	Das *et al*. (2016)
Microfiltration membrane	Single layer	Effluent from electrolysis process	Yun *et al*. (2015)
Microfiltration membrane	Single layer	Oily wastewater	Vasanth *et al*. (2013)
Fabricated ceramic membrane: natural clay			
Microfiltration membrane	Single layer	Dyebath phase of cotton fabric processing unit of a local textile industry	Saini *et al*. (2019)
Microfiltration membrane	Single layer	Tannery wastewater and raw seawater	Mouiya *et al*. (2018)
Microfiltration membrane	Single layer	Agro-food and tannery wastewater	Saja *et al*. (2018)
Ultrafiltration membrane	Multilayer	Synthetic dye filtration (Direct red 80, Acid orange 74 and Methylene blue)	Bouazizi *et al*. (2017)
Microfiltration membrane	Single layer	Clarification of effluent generated by local textile industry, specially washing water effluent of Jean process	Achiou *et al*. (2016)

Microfiltration membrane	Single layer	Industrial wastewater treatment: tannery’s beamhouse section and jean washing process	Bouazizi *et al*. (2016)
Microfiltration membrane	Single layer	Preclarification step in wastewater treatment: treat colored	Elomari *et al*. (2016)
Microfiltration membrane	Single layer	Water treatment	Belibi *et al*. (2015)
Microfiltration membrane	Single layer	Water treatment	Ghouil *et al*. (2015)
Microfiltration membrane	Single layer	Oily wastewater treatment	Kumar *et al*. (2015)
Microfiltration membrane	Single layer	Industrial wastewater treatment	Baraka *et al*. (2014)
Microfiltration membrane	Single layer	Oily wastewater	Abbasi *et al*. (2012)
Microfiltration membrane	Single layer	Water treatment	Bouzerara *et al*. (2012)
Microfiltration membrane	Single layer	Industrial wastewater treatment	Majouli *et al*. (2012)
Microfiltration membrane	Single layer	Removal of chromates from aqueous solutions	Jana *et al*. (2010)
Ultrafiltration membrane	Multilayer	Removal of heavy metal and colorant	Saffaj *et al*. (2010)
Ultrafiltration membrane	Single layer	Wastewater treatment	Masmoudi *et al*. (2007)

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